COMMENTS ON THE DOE TOPICAL REPORT "EVALUATION OF THE POTENTIALLY ADVERSE CONDITION 'EVIDENCE OF EXTREME EROSION DURING THE QUATERNARY PERIOD' AT YUCCA MOUNTAIN, NEVADA"

Prepared for

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1 INTRODUCTION

The Topical Report (TR) is intended to show that there is no evidence of extreme erosion during the Quaternary Period at Yucca Mountain, Nevada. Evidence of extreme erosion is considered a potentially adverse condition for siting of the proposed high-level nuclear waste (HLW) repository as identified at Title 10 of the Code of Federal Regulations, Part 60.122(c)(16) (10 CFR Part 60). The principal evidence used in this TR to reach the conclusion of absence of the potentially adverse condition "evidence of extreme erosion during the Quaternary Period" is provided by boulder deposits on the flanks of Yucca Mountain and neighboring hillslopes. The exposed surfaces of the boulders are coated with desert varnish, which is a black to red-brown manganese-rich coating that accretes on exposed rock surfaces in arid and semiarid regions. It is suggested that older varnishes have a lower ratio of potassium and calcium cations to titanium cations (KCT ratio) than younger varnishes. The oldest varnishes on Yucca Mountain and nearby have been dated by comparing their cation ratios with those of varnishes on materials believed to have a known age. On the basis of these assumptions, the study suggests that boulder deposits on hillslopes in this area have been essentially stable for several hundred thousand to more than one million years. Additionally, local incision of the dated boulder deposits has been relatively insignificant despite the long period of time since their apparent stabilization.

Several assumptions fundamental to the U.S. Department of Energy (DOE) argument, as well as a number of technical aspects of varnish cation dating, have not been adequately discussed. Moreover, the reliance only on *in situ* hillslope deposits does not adequately address other possible aspects of denudation and other erosional phenomena in the area. The geomorphic history and rates of incision of the canyons and washes in the vicinity of Yucca Mountain are of major significance to understanding the character of erosion in the area during the Quaternary.

A study of this type might be able to ascertain whether specific geomorphic surfaces are stable and perhaps provide an indication of their age relative to other local landforms, sediments, or soils provided the precise relationship between the dated material (in this case, desert varnish) and the host material (hillslope boulder deposits) is very carefully determined and reported. Additionally, the dating technique employed in this TR is valid only if it is accurately calibrated with other surfaces and materials which have been dated absolutely. Unfortunately, it appears that neither of the two attributes has been met in this TR. Based solely on information presented and discussed in this TR, it is not possible to demonstrate the absence of extreme erosion at Yucca Mountain and nearby during the 2.0 million years of the Quaternary.

This report has five main components. A narrative of The Center for Nuclear Waste Regulatory Analyses (CNWRA) evaluation of the TR is contained in the main body of the document. Appendix A provides page-by-page evaluation of the TR. Appendix B is a set of detailed comments presented in the standard NRC comment-question format which includes basis, recommendation, and references for each issue raised. Appendix C is a compilation of concerns compiled and delivered to the U.S. Nuclear Regulatory Commission (NRC) early in the TR review process. Appendix D is a discussion of information obtained during the DOE/NRC field trip to the Yucca Mountain vicinity in February, 1994.

2 BACKGROUND

The stated purpose of the DOE investigation of erosion rates at Yucca Mountain is to assess the likelihood of extreme erosion of the land surface within the area immediately above and extending horizontally no more than 5.0 km from the proposed subsurface repository (the controlled area) during the 10,000 yr following closure of the repository. Within the context of this TR, the precise definition of *extreme erosion* is the "occurrence of substantial changes in landforms (as a result of erosion) over relatively short intervals of time" (NRC, 1983: p. 382). It is appropriate to consider the intent of 10 CFR 60.122(c)(16) where the language of the regulation requires an evaluation of the presence or absence of "evidence of extreme erosion during the Quaternary Period." The NRC has defined the Quaternary Period as the past 2.0 million yr (NRC, 1983: p. 373). The DOE internal regulations which define the technical issues pertaining to the guidelines on erosion evaluation are derived from the qualifying and disqualifying conditions of 10 CFR Part 960. Hence, "based on the Quaternary record, are the nature, rates, and depths of erosion such that, when extrapolated for 10,000 yr into the future, they will cause release of radionuclides to the accessible environment that exceed those allowable under 10 CFR 960.4.1?" [(Scientific Application International Corporation (SAIC), 1992: p. 2-72)]. In this context, it is inappropriate to limit this study by adopting an unduly narrow definition of the term *extreme erosion*. The main issue is whether or not the Quaternary record for the area provides any evidence of geomorphic phenomena which indicate that the proposed repository might be compromised over the next 10,000 yr. If any of the potentially adverse conditions is present, it may compromise the performance of the repository. Consequently, in order to show that the repository is not compromised, 10 CFR 60.122(a)(2) requires that the condition must be adequately investigated and its effect adequately evaluated to show that the condition will not significantly affect repository performance (NRC, 1993). It is critical to verify that "erosional processes will not degrade the waste-isolation capabilities of the repository site" and that it "will not be uncovered or otherwise adversely affected by surface-degradation processes" (SAIC, 1992). Denudation rates estimated for the whole of the late Quaternary represent a long-term mean which is not necessarily indicative of conditions over the past 10,000 or 20,000 yr, or indeed the next 10,000 yr. It is essential to consider also the impact of shorter-term geomorphic events. It is particularly important to take into account likely future changes in environmental conditions compared to those of today or the recent past.

In 1992 the CNWRA delivered an evaluation of the Annotated Outline for the TR on extreme erosion to the NRC. Most of the criticisms of the annotated outline for this TR (CNWRA, 1992) have not been addressed in this TR. Of the five main items and issues discussed in the CNWRA report, only one has been addressed, and this only cursorily. First, erosion rates have not been determined on a scale comparable to the 10,000 yr repository life; only very long-term average rates determined for a million or more years have been estimated for the region. Episodes of extreme erosion which may have occurred during the million-plus year period are not addressed. Second, a variety of dating techniques has not been employed. There is a total reliance on the essentially experimental and largely untested varnish cation ratio (VCR) dating technique. Third, nowhere in this TR are likely future rates of erosion discussed; the impact of possible climatic change on rates of weathering and erosion is ignored. Fourth, while the geomorphic impact of tectonic activity in the area is discussed, the effects of possible changes in rates of tectonic uplift are not addressed. And, fifth, the likelihood that human impact will adversely influence erosion rates has not been considered. It must be noted that the breadth of information of the submitted TR is more narrow than the wide-ranging treatment of erosion which was discussed in the annotated outline. Because this TR now only attempts to demonstrate the absence of extreme erosion during the

Quaternary Period, discussions of effects of future erosion, effects of future climate change, and effects of future human activity are not pertinent.

In addition to the CNWRA points, several technical issues concerning VCR dating which were raised by the DOE peer review group (Birkeland et al., 1989) have not been addressed. The review group suggested that further work on the VCR calibration was essential, and that checks on some aspects of the analytical procedures were necessary. Several of these crucial points have not been addressed. These issues will be discussed further in the following sections.

3 GENERAL COMMENTS

The overall organization of the TR could be greatly improved. Much of the introductory material (see sections 3.2 and 3.3 of the TR) would be more appropriate to a discussion of the implications of the results of the investigations — that is, following the presentation of the observational and analytical data. Much of the discussion concerning evidence of Quaternary climatic change presupposes that the varnished boulder deposits are old. For example, it is stated that "the well-developed rock varnish on the boulder surfaces indicates that these hillslope deposits have been stable for relatively long periods...(p. 27)." Also, on p. 21 of the TR "... older varnish is generally darker than young varnish..." Yet there is no discussion of rates of varnish formation or varnish darkening, so the argument is somewhat circular. Moreover, it is subsequently stated that "the absence of colluvial boulder deposits with young varnish coatings on hillslopes in the study area indicates that boulder deposits were not formed during the last glacial episode" (see p. 28 of TR). The fundamental assumption that dark varnish is old has not been tested. As a result, there is a distinct danger that the premise leads to circular reasoning. It follows that if dark varnish is old and the boulder deposits do not have young varnish, all boulder deposits are old. Furthermore, since there is no young varnish on the deposits, there is an implication that the varnish is old too. However, since no physical or chemical data are provided for any *young* varnish in the area, the reasoning is suspect and none of the foregoing assumptions should be accepted without further evaluation.

As was pointed out in the CNWRA comments on the outline for this TR (CNWRA, 1992), a distinction must be made between regional denudation and more localized erosional phenomena. The major portion of the TR deals with dating of hillslope deposits which are presumed to be geomorphically stable. Estimates of rates of incision of channels adjacent to the stable boulder deposits are provided but there is little discussion of rates of incision along the canyons and washes, or of scarp retreat and other backwearing phenomena which are fundamentally distinct from regional lowering of the land surface. While the terms *denudation* and *erosion* are often used interchangeably (for example, Kearey, 1993), for the purposes of this study they should be clearly defined and differentiated.

The DOE has not followed the guidance provided by the NRC in the staff comments on the draft regulation found in NUREG-0804 (NRC, 1983) on the appropriate time interval to be assessed for the Quaternary Period. The NRC has suggested 2.0 million years while the DOE insists upon 1.6 million years. The NRC believes that the selection of 2.0 million years allows for capturing age uncertainty in a discussion of extreme erosion in the Yucca Mountain vicinity. The DOE contends that a period of 1.6 million years is supported by the Geological Society of America.

It is essential to ascertain whether the time periods which are used to calculate the erosion rates during the Quaternary are appropriate for this evaluation of possible evidence of extreme erosion. NUREG-0804 (NRC, 1983: p. 382) defines extreme erosion as the "occurrence of substantial changes in landforms (as a result of erosion) **over relatively short intervals of time**" (emphasis added). Hence, estimates of erosion rates based on net erosion over hundreds of thousands or even millions of years may be inappropriate. It is feasible that much of the incision of a surface which is 500,000 yr old could have occurred over perhaps 10,000 yr or less. If this is the case, the shorter time interval could constitute a period of extreme erosion. However, averaged over a 500,000 yr interval, estimated erosion rates would be 50 times less than the actual rates during the erosional episode. It is inappropriate to assume that the mean conditions which have prevailed over the past million years or so (perhaps 12 million yr in the case of estimated canyon incision rates) will be replicated over the next 10,000 yr. The intent of 10 CFR 60.122 (c) (16) must be carefully considered.

The foregoing observation calls into question the whole concept underlying the approach to this study. By dating stable geomorphic surfaces, the study is more likely to provide an impression of landscape stability than if its focus was the dating of erosional landforms and events. It would be valuable to estimate the likely range in erosion rates by comparing, for example, 1,000 or 10,000 yr of an interpluvial episode (such as the Holocene) with a period of similar length during a pluvial cycle [such as that from about 25 to 15 thousand years before present (kabp)].

Several additional aspects of the TR require elaboration. It is accepted that the purpose of the TR is to evaluate evidence for the incidence of extreme erosion at Yucca Mountain during the Quaternary Period. However, the scope of the investigations of Quaternary denudation around the proposed repository site is far broader. It is impossible to disassociate this study from the broader question of whether "the nature and rates of geomorphic processes that have been operating through the Quaternary Period could, during the first 10,000 years after closure, adversely affect the ability of the geological repository to isolate the waste" (SAIC, 1992: Table 2-7, p. 2-75).

The interpretation that the results of the TR suggest that the late Pleistocene from about 25 to 10 kabp was a period of comparative geomorphic inactivity on the hillslopes of the area must be elucidated. The study not only suggests that very little hillslope erosion occurred during the late Pleistocene but also that there was not a great deal of weathering on the upper hillslopes. This is contrary to some of the evidence from neighboring areas such as the Mojave Desert where Oberlander (1989: p. 71) noted that a late Pleistocene colluvial mantle is currently eroding. This reflects a significant change in geomorphic processes from the late Pleistocene to Holocene time in the Mojave Desert.

It is widely believed that over most of the earth, the Last Glacial Maximum (LGM) at about 18 kabp experienced the lowest mean annual temperatures of any time during the Quaternary. It therefore seems unlikely that frost weathering could have occurred on the upper slopes of Yucca Mountain during the early and middle Pleistocene (as is proposed in the TR) but not at the LGM. This apparent anomaly requires further explanation and corroboration. In the TR, discussion of the variations in mean winter temperatures and the influence of winter precipitation on rates of frost weathering needs clarification and elaboration. In the absence of supporting evidence, it would seem probable that the boulder beds are not as ancient as purported in this study, or perhaps they were formed by processes other than frost weathering. Elsewhere in the southwest United States, the late Pleistocene is represented by significant colluviation on lower hillslopes (Dorn, 1984; Reneau et al., 1986; Dorn et al., 1987) and major changes in the character of pedogenesis (Gile, 1966, 1975, 1977; Gile and Grossman, 1968; and for brief overviews see Hall, 1983; Birkeland, 1992). The climatic conditions experienced in southern Nevada in the late Pleistocene and early Holocene remain uncertain. It would be rash to make assumptions based on evidence from beyond the immediate vicinity. There is a distinct need for further data to corroborate the chronology and paleoenvironmental interpretations presented in this TR.

The absence of boulder deposits from the lower hillslopes on Yucca Mountain is enigmatic. While the phenomenon is not unique (Oberlander, 1989), it does require further consideration. Is it possible that there are boulder deposits on the lower hillslopes but they are buried beneath fine-grained colluvium? If so, what are the implications of a scenario involving exhumation of the boulder deposits on the higher hillslopes? The distinction may simply reflect differences in hillslope erosional processes. Alternatively, it could be indicative of an important aspect of hillslope evolution, or it may have major paleoenvironmental implications.

Nowhere in this TR is the issue of projecting Quaternary rates of erosion to evaluate potential significant effects on isolation of the waste addressed. While this is not strictly within the scope of the document, the intent of 10 CFR 60.122 (a)(2) cannot be ignored. Extrapolation of Quaternary erosion rates into the future must incorporate an evaluation of likely future modifications of antecedent environmental conditions. It must be acknowledged that during the course of the Quaternary it is likely that there have been marked variations in erosion rates which, if they occurred at Yucca Mountain, might significantly affect the waste isolation capability of the site. The first of the two key issues is to assess whether the area has experienced any paleoenvironmental conditions during the Quaternary which resulted in extreme rates of erosion that could threaten waste isolation. Second, it must be determined whether such extreme phenomena or other conditions can be reasonably anticipated at the site in the next 10,000 yr. If erosion rates during the Quaternary can be demonstrated to be benign relative to a potential effect on waste isolation, then the potentially adverse condition 10 CFR 60.122(c)(16) can be said to be absent.

It is unreasonable to assume that a single long-term average rate extending over more than 1 million years of geomorphic activity for the late and middle Quaternary is likely to prevail for the next 10,000 yr, especially given the exaggerated fluctuations in environmental conditions over the past 25,000 yr or so (Spaulding, 1985). Of critical importance is a consideration of maximum short-term erosion rates found in the region and the likelihood of their occurrence at Yucca Mountain sometime during the regulatory period of interest.

The nature of the relief of Yucca Mountain (about 400 m of local relief), possible changing rates of tectonic uplift which changes geomorphic base level, varying rates of bedrock weathering (i.e., due to climatic change), and the nature of the unlithified surficial materials, are all critical parameters in any estimation of likely future rates of denudation or incision within the area. The information provided concerning the sediments of Fortymile Wash suggest potential base levels more than 100 m below present (the depth of the alluvial fill at borehole J-13). Excavation of this unlithified valley fill would lower the land surface in Fortymile Wash to within about 170 m of the repository horizon. A burial depth of greater than 300 m is deemed favorable by the NRC, so the potential diminution of burial depth to 170 m or less and the plausible effects on waste isolation should be mentioned and appropriately dealt with in the TR. According to the first scenario presented in Figure 13 of the TR, this excavation of valley fill in Fortymile Wash may have occurred within the past 10,000 yr or so, with subsequent sedimentation having filled the excavated channel. In order to understand the erosion rates and processes, it is essential to consider the sources of the valley fill, and also to where the eroded material is evacuated, when these cut-and-fill events occur. In addition, the depth of cover from the base of Solitario Canyon to the repository horizon is only 70 m vertical relative to the elevation of the west end of the repository. Possible erosion of 70 m magnitude depth in Solitario Canyon would be considered a potentially adverse condition.

It would be valuable to attempt to estimate the volumes of colluvial and alluvial material stored on the lower hillslopes and pediments, and in the canyons and washes in the vicinity of Yucca Mountain. While such estimates would necessarily be very approximate, they should provide a general indication of basin-wide rates of weathering and erosion (e.g., Dardis, 1990). These estimates could be used to check the long-term erosion rates indicated by the VCR studies. Clearly, the sources of the sediments are a critical issue. Some late Quaternary alluvium, for example, is probably reworked older colluvial and alluvial material. While the original source of much this material was undoubtedly hillside alluvium and colluvium, it may have been stored on lower hillslopes or as older alluvium for an indefinite period. Moreover, some sediment may originate beyond the immediate catchment, having been deposited as atmospheric fallout.

4 METHODOLOGICAL ISSUES

This section contains a discussion of the methods used in various parts of the TR to demonstrate the lack of extreme erosion during the Quaternary Period in the Yucca Mountain vicinity.

4.1 EROSIONAL SURFACE DATING

The premise that long-term erosion rates can be estimated from the depth of incision of dated, stable geomorphic surfaces must be validated. Since it is the stable surface that is dated and not the erosional landform, it is uncertain when erosion commenced. Moreover, because erosion rates were determined over a very long interval of time, there is a distinct possibility that the occurrence of accelerated or even catastrophic erosional events is overlooked.

4.2 DENUDATION RATES

The section of the TR which deals with reported denudation rates from other areas with similar climates and also other areas of North America is sometimes misleading. The intent of providing these data and the accompanying discussion is evidently to show that the erosion rates determined for Yucca Mountain using the VCR dating technique are very low in comparison to most arid and semi-arid regions. However, since there is an abundance of data concerning this issue (much of which cannot be cited simply because of constraints of space and time), it should be stressed that the information provided in the TR is merely a representative sample. Certain data have been omitted even from the cited sources [for example, additional data from less arid parts of Australia quoted by Bishop (1985)].

It would be far more valuable to provide some additional information on, for example, how variations in relief affect erosion rates, or how rates of weathering may influence rates of erosion on different lithologies under various climatic regimes. Some of this material has been discussed by Summerfield (1991) who provided a succinct overview of global-and continental-scale denudation rates and the ways in which local factors can influence differential rates of erosion. In this context, it is important to address the issue of potential rates of regional denudation and more localized erosional incision of the landscape. Variations in local relief, changes in base levels resulting from tectonic activity, the impact of climatic change on weathering rates, and the physical and chemical properties of both the lithified and unlithified surface materials are all significant influences on rates of erosion.

It is important to realize that regional denudation can result from many diverse processes. In temperate regions of the northern hemisphere, glaciation has commonly had a brief, but very dramatic, impact on long-term erosion rates. In the tropics, notably in Africa and Australia, some land surfaces appear to have been essentially stable for over 100 million yr or more. Even here, however, chemical denudation as a result of subsurface weathering has lowered apparently relict landscapes by several tens of meters (Tardy, 1992; Tardy and Roquin, 1992). Similar chemical denudation occurs in many areas of limestone bedrock, though its surface expression is both more idiosyncratic and pronounced. In the case of Yucca Mountain, it is important to consider whether hillslope lowering is a representative process in regional denudation. Backwearing of the hillslopes and mountain sides by peripheral scarp retreat along canyons or fault-bounded free-faces may be more significant. Investigations of the geomorphic stability of upper hillslopes would tend to overlook such processes or minimize their importance in terms of the regional denudation chronology. Similarly, low areas currently mantled by thick colluvial, alluvial, and eolian deposits may be potentially more susceptible to incision as a result of erosion by streams and rivers under suitable conditions. An investigation of current and potential regional base levels in Fortymile Wash and the Amargosa River basin should clarify some of these issues of the potential erodibility of the land surface.

4.3 STRATIGRAPHIC RELATIONSHIPS

The stratigraphic associations, as well as the physical and chemical properties of the surficial materials within and adjacent to the controlled area, must be described in greater detail. The information presented by Swadley et al. (1984) and Hoover (1989), as well as earlier studies, provides much baseline data. However, more work is required to evaluate the implications these data have on an assessment of the likelihood of there having been extreme erosion during the Quaternary, or whether such conditions are likely to occur in the future. The map presented by Swadley et al. (1984) that is the source of Figure 7 of the TR, does not provide information on the distribution of colluvial hillslope deposits. In addition, the stratigraphic interpretations and ages of the deposits are largely tentative, being based on limited field observations and uranium-trend dating that is of uncertain accuracy.

Additional information on the thickness of the various sedimentary deposits would be especially valuable. The information from borehole J-13 as presented in Figure 13 is inconclusive but does indicate that substantial volumes of sediment have been mobilized during the middle and late Quaternary. The sources of the sediment and mode of mobilization should be carefully considered in the context of possible evidence of extreme erosion during the Quaternary Period (Swadley et al., 1984).

The morphology of the hillslopes of Yucca Mountain area is largely controlled by the lithology. In effect, the hillsides are apparently weathering-limited slopes (Cooke et al., 1993). Hence, temporal variations in the rates of weathering on the hillslopes are of major significance because they determine potential erosion rates. In effect, the likelihood of extreme erosional events occurring on upper hillslopes is predicated as much by antecedent weathering phenomena as by specific erosional processes. However, this situation does not apply to the lower hillslopes, pediments, and valley floors where there are thick colluvial and alluvial accumulations. Here, the factors limiting potential erosion include vegetation cover, local and regional base levels, the properties of the surface materials, and the actual erosivity of eolian and fluvial processes.

4.4 VALIDITY OF CATION-RATIO DATING METHOD

The cation-ratio dating method was developed as a technique for dating the interval of time Quaternary deposits have remained exposed in an arid to semi-arid climate. As the author(s) of this TR clearly state in Section 3.3.2.1 and elsewhere in the TR, the complex processes that produce variations in the composition of rock varnish with time are not completely understood. However, further discussion of the limitations of the cation-ratio dating technique are required before the presented dates can be rigorously accepted as age estimates.

The VCR dating technique has received considerable attention since it was first proposed and developed by Dorn (1983). Despite a considerable amount of work on the physical and chemical properties of desert varnish (Perry and Adams, 1978; Potter and Rossman, 1979; Krumbein and Jens, 1981; Dorn and Oberlander, 1982; Dorn, 1984; 1990; 1992), the exact reasons for apparent variations in the molar ratio of [(K+Ca)/Ti] (KCT) are obscure.

There are three primary models to account for variations in minor element abundances in rock varnish with time. A widely held model is that relatively mobile K and Ca are preferentially leached from accreting varnish while Ti remains immobile, resulting in lower KCT with time (e.g., Dorn, 1983; Dorn and Krinsley, 1991; Dorn and Phillips, 1991). However, Reneau et al. (1992) concluded that variations in the composition of detrital mineral grains and authigenic mineralization strongly influence the composition of rock varnish, and that these variations invalidate the basic premises of the VCR dating technique. In addition, Reneau and Raymond (1991) and Bierman and Gillespie (1994) have observed that minor element variations in rock varnish were inconsistent with a leaching hypothesis. Instead, they postulated that observed KCT relationships reflect the preferential incorporation of host-rock fragments, which have high KCT ratios, into thin, young varnish deposits. Older, thicker deposits contained relatively fewer host-rock fragments and thus have lower KCT ratios. However, the results of these studies indicate that the amount of substrate incorporation does not vary regularly with time.

If the host rocks for the dated varnish deposits have similar lithologies (i.e., composition, mineralogy, texture), then KCT ratios may vary uniformly with time for these deposits (i.e., Dorn, 1983). However, if different host lithologies are present, then different KCT ratios could be incorporated into the analyzed varnish deposits. This observation is especially significant for the Yucca Mountain region because different host lithologies are used in both calibration standards and dated samples.

Basaltic rocks in the Yucca Mountain region have KCT ratios that are between about 10 to 13 (Table 4-1). These basalts are the primary host for dated varnish deposits at Skull Mountain, Little Skull Mountain, Buckboard Mesa, and Crater Flat. However, talus deposits at Yucca Mountain consist of fragments of welded rhyolitic ignimbrite, which are primarily from the Tiva Canyon member of the Paintbrush Tuff (U.S. Department Of Energy, 1988). KCT ratios for Tiva Canyon rhyolite are about 60, but decrease to about 30 for less abundant quartz latite members (Broxton et al., 1989). These ignimbrites also are the dominant lithologies in the alluvial deposits used to construct part of the cation-ratio calibration curve for Yucca Mountain (Harrington and Whitney, 1987; Whitney and Harrington, 1993). Thus, two distinct lithologies (basaltic lava and welded rhyolitic ignimbrite) are used to construct the cation-ratio calibration curve for Yucca Mountain.

If the hypothesis of Reneau and Raymond (1991) and Bierman and Gillespie (1994) is accepted, then a linear relationship may not exist between the 40–255 ka ignimbrite hosts and the 1.1-Ma basaltic hosts on the Yucca Mountain cation-ratio calibration curve. The KCT ratios of these two lithologies should represent two different cation-ratio trends that originate at different initial KCT ratios that reflect the different host lithologies. In addition, measured KCT ratio variations on samples of unknown age may reflect variations in the amount of substrate fragments incorporated into the varnish and not accurately represent the age of the deposit.

In addition to potential uncertainties caused by variations in host-rock lithology, Dorn et al. (1989), Krinsley et al. (1990), and Dorn and Krinsley (1991) have shown that different types of rock varnish may be present in an area, of which only some are suitable for cation-ratio dating. The TR does not address how different types of rock varnish were recognized, nor if different types of varnish textures were present in the studied rocks. This is significant because Dorn and Krinsley (1991) measured KCT ratios at the Little Cone volcano, which is part of the Quaternary volcanic alignment that includes Black Cone and Red Cone (e.g., Vaniman et al., 1982). KCT ratios for Little Cone layered-texture varnish are 2.7 ± 0.2 at 1 σ uncertainties, which is comparable to reported values of 2.2 ± 0.3 and 2.3 ± 0.1 for Black Cone and Red Cone, respectively (Harrington and Whitney, 1987). However, porous-texture varnish at Little Cone has a KCT ratio of 1.9 ± 0.4. Although the Dorn and Krinsley (1991) values are each within

Table 4-1. KCT ratios for basaltic rocks in Yucca Mountain region, Nevada

	Weight Percent			ppm	Mole Percent					
Crowe et al., 1986	**TiO2**	**CaO**	**K2O**	**Ba**	**Ti**	**Ca**	**K**	**Ba**	**K+Ca/Ti**	$\frac{K+Ca}{Ti+0.33\ Ba}$
Black Cone	1.50	8.90	1.60	1220	0.017	0.16	0.03	0.003	11	11
Red Cone	1.30	9.00	1.60	1400	0.015	0.16	0.03	0.003	13	13
Buckboard Mesa	1.50	7.00	2.30	2100	0.017	0.12	0.05	0.003	10	10
Little Skull Basalt	1.55	10.67	0.92	1024	0.018	0.19	0.02	0.003	12	12
Little Skull B And	1.28	8.20	1.74	821	0.015	0.15	0.04	0.003	12	12
Broxton et al., 1989										
Tiva Rhyolite	0.14	0.26	4.74	51	0.002	0.005	0.10	0.003	65	64
Tiva QTZ Latite	0.48	1.69	5.70	2098	0.006	0.03	0.12	0.003	27	25

the range of 1σ error reported for Black and Red Cones, the Little Cone data indicate that Black and Red Cone KCT ratios could be mixtures of layered-texture and porous-texture varnish. Similar textural variations likely affect KCT ratios in other deposits (Dorn and Krinsley, 1991). Thus, textural variations in varnish may produce some of the KCT variations attributed solely to age. The relationship between varnish texture and KCT ratio is not discussed in the TR.

Based on the requirements of this TR on Quaternary erosion, cation-ratio dating of rock varnish appears to be the only technique suitable for dating coarse unconsolidated talus deposits of varying lithology. However, potential limitations to the technique involving variations in host lithology and varnish-texture heterogeneity are not discussed, and could significantly affect the precision and accuracy of the reported cation-ratio dates. Further discussion of these potential limitations is required before the proposed dates can be rigorously accepted as ages for these hillslope deposits.

4.5 SOLE RELIANCE ON VARIABLE CATION RATIO DATING

The TR relies almost exclusively on one dating technique to determine the age of deposits and geomorphic surfaces, and thereby ascertain long-term erosion rates. This technique involves determination of the desert VCR of coated boulder deposits, and comparison of these ratios with those from varnishes on deposits of known age. The possible shortcomings of the technique are outlined in the following. These notwithstanding, there is a danger that, by using this procedure without adequate corroboration, significant misinterpretations could occur.

While depletion of potassium and calcium in older varnish may be a result of cation leaching (Dorn and Krinsley, 1991), it has been suggested that the incorporation of particles of host rock (also commonly termed substrate) may account for the variations. Reneau and Raymond (1991) argued that some cation determinations for thin varnish coatings may inadvertently include substrate in the analyses (usually resulting in erroneously high KCT ratios). They suggested that variations in KCT ratios may be independent of varnish age except that older varnishes, which are commonly thicker, are less likely to have unduly high levels of incorporated substrate. This would accord them a comparatively low KCT ratio.

While some of these issues have been addressed in the TR, it is clear that the VCR dating technique requires further investigation before its validity can be confirmed. Even over the past 2 or 3 yr, some significant changes in the analytical procedures have been advocated (for example, Bierman and Gillespie, 1991; Harrington et al., 1991). Moreover, some of these have not been adopted in this study and TR. In effect, it would be rash to rely exclusively on this essentially poorly understood technique. Other varnish dating methods have been proposed, though most of these are also largely experimental. They include radiocarbon dating procedures (Dorn et al., 1986) and $^{230}Th/^{234}U$ (corroborated using $^{231}Pa/^{235}U$) (Knauss and Ku, 1980). In addition, techniques such as thermoluminescence (TL) dating, uranium-series, as well as other radiometric techniques, would be suitable for dating materials associated with the boulder deposits and other sediments (see, for example, Whitney and Harrington, 1993). Indeed, uranium-trend ages are used to obtain absolute dates for three points on the calibration curve used for VCR dating in this study. Hence, at least in principal, this technique could also be used for direct corroboration of some of the VCR ages.

Simply because VCR dating in itself appears to be suitable for dating material spanning a broad time period (much of the Quaternary) and also appears to be appropriate for dating boulder deposits does not justify its use to the exclusion of other dating methods. Other geomorphic surfaces and deposits can, and should, be dated in order to substantiate the VCR dates obtained for the boulder deposits. There is a danger that the TR provides a restrictively narrow view of landscape evolution since it focuses mainly on just one geomorphic unit (*in situ* hillslope deposits). A more convincing and demonstrable argument could be presented if the palaeoenvironmental chronology for the area was reconstructed using a variety of techniques to date (both relatively and absolutely) a suite of surfaces and associated materials while providing the basis for a well-rounded, thorough, and inclusive discussion of any extreme erosion within the geologic setting. The work of Swadley et al. (1984), Hoover (1989), and earlier workers provides much of the valuable information needed to achieve this goal. As it stands, however, the present study is not well integrated with the earlier work despite being heavily reliant on it for determining the VCR calibration curve.

4.6 BOULDER SAMPLING METHODS AND ANALYSES

About 20 large boulders in each deposit were sampled, and 8 to 10 of the best of these samples were selected for analysis. Were multiple samples from the same boulder collected and analyzed? In the sample preparation section it is stated that two samples from each boulder were analyzed when possible. In the sample analysis section, six overlapping sites per sample disk were analyzed by Scanning Electron Microscopy Energy Dispersive Spectromety (SEM EDS). It would be very useful to see the data for these analyses, instead of only the summaries in Table 4 of the TR. These data could be used to address questions about, for example, what proportions of the variation in KCT ratio are due to sample disk variability, interdisk variability for each boulder, and intraboulder variability for each deposit. This information is important for evaluating the presented data summaries, and for independent calculations of analytical uncertainties and sample homogeneity.

As stated in the TR, Harrington and Whitney (1987) noted that similar lithologic substrates are necessary to avoid potential variations in varnish thickness and composition. The Tiva Canyon ignimbrite is moderately to densely welded and sparsely phyric. Matrix glass has been recrystallized to mixtures of cristobalite and alkali feldspar (e.g., Bish and Chipera, 1989). However, basalt in the study area generally has a crystalline groundmass that consists of plagioclase, olivine, pyroxene and Fe-Ti oxides (e.g., Vaniman et al., 1982). The two substrates are significantly different. It is not clear why the processes of varnish deposition and cation leaching should be the same for these two mineralogically and texturally distinct lithologies.

4.7 VALIDITY OF CALIBRATION METHOD

As stated in section 3.3.2.1.2 in the TR, two different lithologies are used to create the calibration curve. A linear relationship may not exist between these two calibration points in the interval between 255 ± 15 ka and about 1.1 Ma. The presence of a linear relationship must be explicitly determined, because most of the data in the TR have KCT ratios between the calibration points (i.e., ages presumed to be between 0.3 and 1 Ma). Additionally, the study is biased toward other samples in that the calibration curve can only extend to 40 kabp.

The K-Ar dates for Black and Red Cones, which are used to construct the calibration curve, may not be as precise and accurate as reported. Red Cone has numerous K-Ar dates besides the 1.12 ± 0.07 Ma listed in Harrington and Whitney (1987), which range from 0.95 ± 0.11 to 1.9 ± 0.2 Ma (Sinnock and Easterling, 1983; Vaniman et al., 1982). Black Cone also was dated at 1.1 ± 0.4 Ma

(Vaniman et al., 1982), in addition to the 1.1±0.3 Ma date in Harrington and Whitney (1987). No criteria are presented in the original reference (Harrington and Whitney, 1987) or subsequent reports (Whitney and Harrington, 1993) on why 1.12±0.07 Ma and 1.1±0.3 Ma are selected as the respective ages of Red and Black Cones. Although these dates are the same at 1σ uncertainties, changes in the magnitude of uncertainty between these two dates (i.e., 100 ky) may affect the error associated with the VCR calibration curve.

The TR text concludes that the uranium-trend dates on Crater Flat alluvium do reflect the age of deposition. However, the CNWRA believes that uranium-trend dates on alluvium in Crater Flat and Fortymile Wash do not necessarily reflect the age of deposition of these units, as erroneously stated in the text of the TR (p. 36). In the TR, three of the five calibration points are dated using uranium-trend methods. Swadley et al. (1984) used these same dates to estimate the ages of Quaternary soils and alluvial deposits in the vicinity of Yucca Mountain. They noted that the dating method was experimental and "that accuracy of the absolute ages derived by this method is not known..." (Swadley et al., 1984: p. 6). Geyh and Schleicher (1990: p. 226) also question whether uranium-trend dates actually represent the age of the deposit. No data have been presented in the TR to demonstrate that the uranium-trend dates used in the calibration curve either precisely or accurately represent the age of the varnish associated with these deposits. Although Harrington et al. (1988: p. 1052) stated that the "analytical uncertainty in the K-Ar and U-series dates is minimal," the Los Alamos National Laboratory peer-review group felt that "additional calibration points should use all suitable methods" (Birkeland et al., 1989: p. 6). The VCR calibration curve used for this study apparently has not been modified or tested in any way since it was originally published by Harrington and Whitney (1987).

It is not possible to directly correlate the samples dated by the uranium-trend method (Rosholt et al., 1985) with calibration units Q2c, Q2b, and CF, using the limited data presented in the TR or associated publications. Although unpublished uranium-trend dates by Muhs are used in Table 1 of Harrington and Whitney (1987), these dates are not presented in the topical report and cannot be evaluated for precision or accuracy. Numerous sites for units Q2c, Q2b, and CF are presented in Rosholt et al. (1985), but there is no discussion of the range in apparent ages of these units in Harrington and Whitney (1987). The 40±10 ka "Crater Flat surface" reported in Harrington and Whitney (1987) apparently corresponds to unit Q2a in Rosholt et al. (1985), which has an apparent range in age from 30±10 to 55±20 ka in the Yucca Mountain area. Unit Q2b, which has a reported age of 160±20 ka in Harrington and Whitney (1987), ranges in age from 160±25 to 200±80 ka in Rosholt et al. (1985). Unit Q2c, which has a reported age of 255±15 ka in Harrington and Whitney (1987), ranges in age from 240±50 to 310±40 ka for the upper member reported in Rosholt et al. (1985). Clearly, the precision and accuracy of the dates associated with units Q2c, Q2b, and CF is significantly lower than reported in Harrington and Whitney (1987).

Rosholt et al. (1985) report that gravels in the upper member of unit Q2c "locally overlie and contain reworked cinders from the Big Dune basalt center 11 km northwest of Lathrop Wells," Nevada. Although earlier K-Ar dates for this volcano (Vaniman et al., 1982) are between 200 and 300 ka, these dates are generally regarded as erroneously old (e.g., Crowe et al., 1992). Relatively high-precision Ar-Ar (Turrin et al., 1991) and cosmic-ray exposure dates (e.g., Crowe et al., 1992; Zreda et al., 1993) indicate that the age of the "Big Dune" volcano is likely 100±50 ka. Thus, unit Q2c should be significantly younger that the 255±15 ka age used in the VCR calibration curve for the TR. Likewise, the ages of units Q2b and CF may also be significantly younger than represented by the uranium-series dates.

The original source of the calibration data in the TR is thought to be Harrington and Whitney (1987). However, the errors in the KCT ratios reported in Harrington and Whitney (1987) are significantly larger than those presented in this TR (Figure 9) or Whitney and Harrington (1993) (Figure 8). Analytical methods presented in this TR appear identical to those used by Harrington and Whitney (1987) and Whitney and Harrington [(1993), Figure 8.] It is thus not clear why analytical errors are roughly 75 percent lower in this TR than in the original reference (Harrington and Whitney, 1987). (Figure 4-1).

4.8 CALCULATION OF UNCERTAINTIES IN THE VARNISH CATION-RATIO DATING METHODOLOGY

It is not possible to evaluate rigorously the uncertainties and dates presented in Table 4 of this TR without knowing the analytical uncertainty associated with the KCT analyses. Bierman et al. (1991) noted that for SEM-EDS analyses of rock varnish, analytical uncertainty in the KCT ratio is about 10 percent for count times of 200 s. This uncertainty was determined on the same type of EDS system used in the TR analyses, with a 15-kev accelerating voltage and a 10 nA beam current on the SEM. In this TR, accelerating voltages apparently ranged from 15 keV for Crater Flat analyses to 30 keV for Black and Red Cone analyses, resulting in detector dead-times of 15–20 percent for count times of 150 s (Harrington and Whitney, 1987). Although Bierman et al. (1991) do not report detector dead-times, their analytical conditions appear very similar to those used in this TR (Table 4) and thus analytical errors may be about 10 percent for the KCT ratios.

Harrington and Whitney (1987) report that replicate analyses of 22 samples gave KCT ratios that varied about 4 percent between two analytical runs. This error does not represent the uncertainty associated with the KCT analyses, but rather reflects the reproducibility of the analyses. Individual KCT analyses have reported analytical errors that range between 5 and 24 percent and average 14 percent (Table 4-2) (Harrington and Whitney, 1987). In addition, cation ratios by Reneau et al. (1992) were determined by analytical methods that are very similar to those apparently used in the TR, and have approximate analytical precisions of 5 percent for K, 7 percent for Ca, and 13 percent for Ti. This analytical error is consistent with a 10-percent error generally associated with SEM-EDS analyses for K, Ca, and Ti (Bierman et al., 1991; Reneau et al., 1992).

Uncertainties for KCT ratios used to calculate dates in this TR do not accurately represent the uncertainties in the analytical data. Two measures of uncertainty are provided in Table 4 of the TR: the standard deviation of the mean KCT ratio for a deposit (S_{CR}) and a 95 percent confidence level (CL) for the mean cation ratio (95-percent CL), calculated from Bierman et al. (1991). Average uncertainties in the KCT ratio are 9 percent for the S_{CR} of the Yucca Mountain region data, but decrease to 3 percent using the 95-percent CL (Table 4-2). The 95-percent CL value is then used to calculate the uncertainty in the cation-ratio dates because it is believed to more accurately measure the true uncertainty in the KCT ratio than S_{CR} (TR; Bierman et al., 1991; Whitney and Harrington, 1993). However, neither of these uncertainties incorporate analytical error (≈ 10 percent) in their calculation and thus do not accurately reflect the uncertainties in the KCT ratios.

A more accurate determination of the mean and standard deviation of a data set can be calculated by propagating n sample analytical errors ($X_i \pm x_i$) through the basic statistical calculations

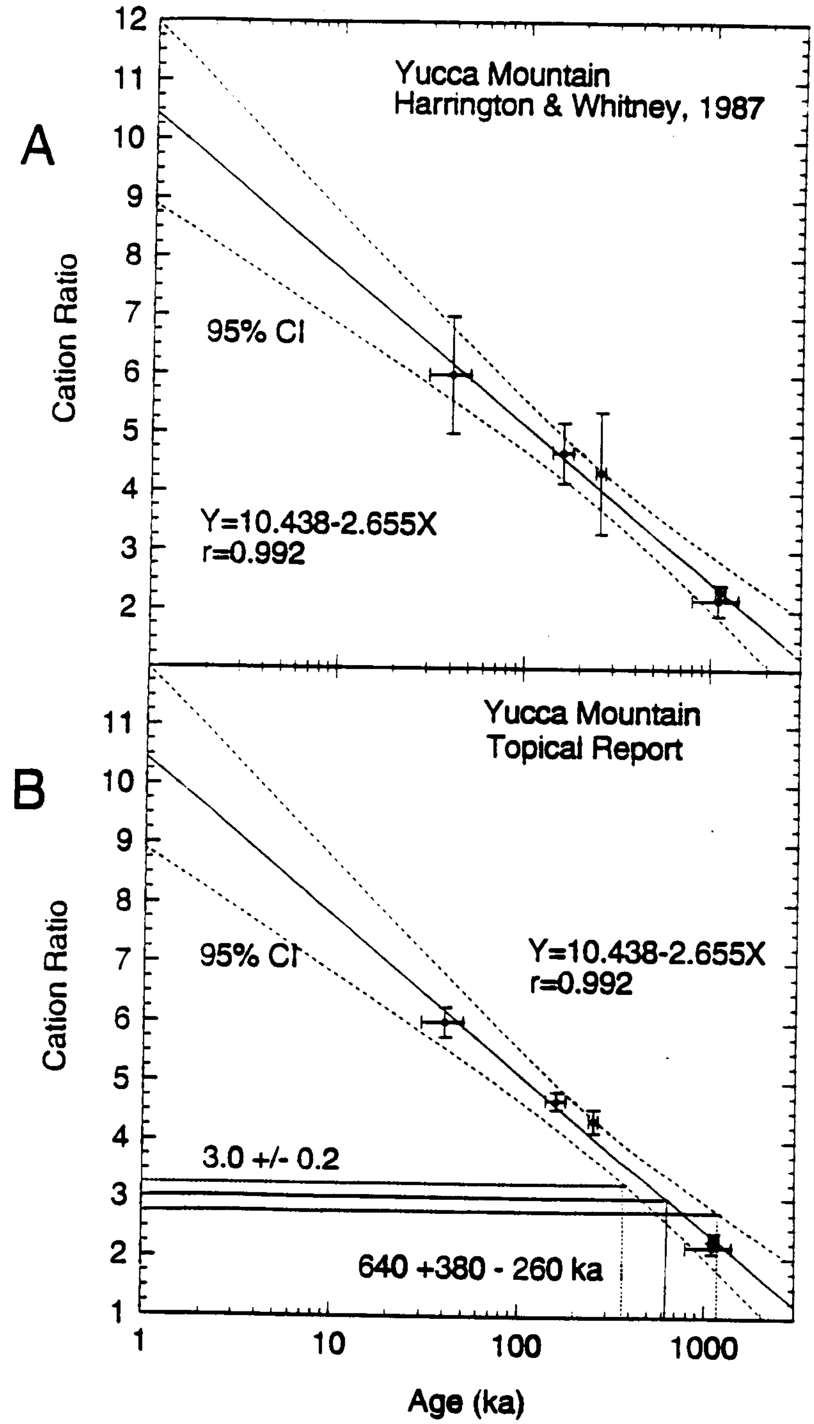


Figure 4-1. (A) VCR dates and uncertainties from Harrington and Whitney (1987). Cation ratios for these samples are 75 percent smaller in the TR (Figure 4-1B). (B) Uncertainty in the scope of the calibration curve (estimated by a 95 percent confidence interval) affects date uncertainty significantly.

Table 4-2. Cation-Ratio dates from Whitney and Harrington (1993) and Erosion Topical Report.

Unit	Sample	Reported # Sites	KCT	1 Scr	95%CL		Calculated %Error in KCT (KCT/Err) w/ 1 Scr	w/ 95%CL
Yucca Mtn	YME-1	55	2.99	0.19	0.05		6	2
Yucca Mtn	YME-2	80	4.52	0.55	0.12		12	3
Yucca Mtn	YMW-1	55	3.34	0.47	0.13		14	4
Yucca Mtn	YMW-2	40	2.97	0.08	0.03		3	1
Yucca Mtn	YMW-3	65	2.88	0.19	0.05		7	2
Yucca Mtn	YMN-1	40	2.79	0.27	0.09		10	3
L. Skull Mtn	LSM-1	160	2.52	0.21	0.03		8	1
Skull Mtn	SKM-1	45	2.74	0.21	0.06		8	2
Skull Mtn	SKM-2	30	2.68	0.16	0.06		6	2
Skull Mtn	SKM-3	35	2.28	0.26	0.09		11	4
Skull Mtn	SKM-3A	50	2.49	0.11	0.03		4	1
Buckboard Mesa	BM-1	40	2.09	0.35	0.11		17	5
						Average	9	3

Calculations using calibration from Harrington & Whitney (1987): (KCT=10.466-2.667 log t) and above data

Unit	Sample	Reported Date (ka)	Range	Calculated date w/ 95%CL ka	-1s	+1s	Avg %Err		Calculated date w/ Scr ka	-1s	+1s	Avg %Err
Yucca Mtn	YME-1	640	610-670	640	610	660	4		640	540	750	16
Yucca Mtn	YME-2	170	140-180	170	150	190	12		170	110	270	47
Yucca Mtn	YMW-1	465	400-515	470	420	520	11		470	310	700	41
Yucca Mtn	YMW-2	645	630-660	650	630	660	2		650	600	690	7
Yucca Mtn	YMW-3	710	680-740	700	670	730	4		700	590	820	16
Yucca Mtn	YMN-1	760	710-820	760	700	810	7		760	600	950	23
L. Skull Mtn	LSM-1	960	930-990	950	930	980	3		950	800	1140	18
Skull Mtn	SKM-1	800	760-830	790	750	830	5		790	660	950	18
Skull Mtn	SKM-2	830	800-880	830	790	870	5		830	720	950	14
Skull Mtn	SKM-3	1180	1110-1270	1170	1090	1270	8		1170	940	1470	23
Skull Mtn	SKM-3A	990	960-1030	980	950	1010	3		980	890	1080	10
Buckboard Mesa	BM-1	1380	1260-1510	1380	1250	1520	10		1380	1020	1870	31
						Average	6					22

Representative analyses:		Harrington & Whitney (1987) KCT	Std Error	%Err		Whitney & Harrington (1993) (Estimated uncertainties from error bars) KCT	± Err	%Err
Yucca Mtn	BC	2.18	0.27	12		2.18	0.10	5
Yucca Mtn	RC	2.33	0.11	5		2.33	0.10	4
Yucca Mtn	Q2c	4.34	1.04	24		4.34	0.20	5
Yucca Mtn	Q2b	4.68	0.52	11		4.68	0.15	3
Yucca Mtn	CF	6.00	1.00	17		6.00	0.25	4
			Average	14				4

$$\overline{X} \pm \overline{x} = \frac{\sum X_i}{n} \pm \frac{\sqrt{\left(\sum x_i^2\right)}}{n} \tag{4-1}$$

where $\overline{x}$ = Uncertainty in the average (i.e., σ_{CR})

$\overline{X}$ = Average of n samples

and

$$\text{Sdev} = \sqrt{\frac{\sum \left(X_i \pm x_i - \overline{X} \pm \overline{x}\right)^2}{n - 1}} \tag{4-2}$$

The uncertainty associated with the mean KCT ratio will thus increase when analytical error is propagated, but this value will more accurately represent the error associated with the KCT analyses than a standard deviation calculated without propagation of analytical error. The reported S_{CR} values (Table 4-2) thus underestimate the standard deviation of the KCT analyses because analytical error has not been propagated through the calculations.

On this basis, the uncertainties in the KCT ratios from this TR cannot be accepted as an accurate representation of the uncertainty in the analyses used to determine these ratios. The reported uncertainties underestimate the uncertainties most likely associated with these data. The 95-percent CL values (Table 4-2) also underestimate KCT uncertainty, because these values incorporate S_{CR} in their calculation (Bierman et al., 1991). The individual analyses for each of the 12 sample sites thus must be provided before the true uncertainty associated with the cation-ratio dates can be determined. As a minimum estimate of uncertainty, dates should be calculated using the S_{CR} errors reported for these analyses (Table 4-2).

As was discussed by Harden et al. (1988), the calibration curve used to calculate cation-ratio dates does not represent the uncertainty associated with the data used to construct the curve. Each of the five data points used in the calibration curve have an uncertainty associated with the measured KCT ratio and the age of the deposit. This uncertainty must be incorporated into all date calculations, and cannot be simply ignored because a correlation coefficient of 0.992 is determined on the linear regression (Harrington and Whitney, 1987).

The uncertainty in the calibration curve cannot be accurately determined from the data presented in the TR. As noted above, the error bars in Figure 9 of the TR are 75 percent smaller than in the source of the original data (Harrington and Whitney, 1987). However, one estimate of the uncertainty in a linear correlation can be determined by calculating a 95-percent confidence interval, which is based on the standard deviation of the data set. The 95-percent confidence intervals for the Yucca Mountain calibration curves (Figures 4-1A, B) were calculated using the SigmaPlot (Version 5.0, 1992) statistics program. For a KCT ratio of 2.99 ± 0.19 (TR, sample YME-1), this apparent uncertainty in the calibration curve results in a date uncertainty that increases from the reported value of ± 30 to $+380$ or -260 ka (Figure 4-1B).

4.9 QUATERNARY HISTORY OF FORTYMILE WASH

The section of the TR dealing with the alluvial deposits along Fortymile Wash is inconclusive. Two very different scenarios for Quaternary alluviation are presented in Figure 13 of the TR. The implications that each of these scenarios has on interpreting late Pleistocene geomorphic activity are markedly different.

The implications of the first model are that there was major Pleistocene incision (108 m below the current bed of the wash) and subsequent aggradation during the Holocene. A key issue here is the provenance of the Holocene alluvium. If hillslope erosion provides the material, the long-term stability of these surfaces is called into question. If the Holocene alluvium is older alluvium which has been reworked, the source must be elucidated because excavation of Quaternary alluvia might indicate rapid erosion at certain times during the late Quaternary.

The implications of the second model presented in Figure 13 of the TR are equally profound. The presence of large volumes of mid-Pleistocene alluvium is in itself important, particularly when its likely origins are considered. Furthermore, the absence of any subsequent major sedimentation during the late Quaternary is an important phenomenon. The likelihood that the late Pleistocene and the Holocene were periods of relative geomorphic inactivity in comparison with the early and middle Quaternary is of fundamental importance to the denudation chronology proposed in the TR. While this model appears to fit the evidence relating to the hillslope boulder deposits, the TR does not offer supporting documentation for such a paleoenvironmental history.

5 TECHNICAL ISSUES

Notwithstanding the importance of the criticisms of the methodological approach adopted in this study of extreme erosion at Yucca Mountain, there are a number of more fundamental technical issues which have not been adequately addressed. There are shortcomings in some aspects of the technical approach that are so significant that both the rationale used and the results of the study must be questioned. A technically rigorous study should include demonstration of the following:

- Representativeness of the age of the deposits on which dated varnish is found, and proof that these deposits represent stable geomorphic surfaces
- Accuracy and preciseness of determination of VCR
- Validation of calibration curves used to derive absolute ages from the VCR data
- Validation of calculations of rates of erosion (based on the purported age of the varnish) within the scope of the study
- Quantification of uncertainties in data and model precisions and accuracies
- Presentation and discussion of VCR data to enable a rigorous scrutiny
- Determination of both long-term and short-term erosion rates

5.1 VERIFICATION OF WHAT IS BEING DATED

It is essential to verify what is actually being dated by the VCR dating procedure. The contention that the hillslope boulder deposits represent stable geomorphic surfaces is central to the whole study. This assumption must by thoroughly tested. The following are points which should be addressed:

- Varnish preservation on boulders moving by creep or other gentle mass-wasting processes

  Examples of "dry block creep" have been described in some desert environments (Cooke et al., 1993). Hence, hillslope mass-wasting phenomena are not necessarily confined to more humid regions or periods of wetter or colder climatic conditions.

  In the TR it is argued that the varnish coatings are too fragile to be preserved on moving boulders. However, elsewhere in the TR, it is stated that the varnish protects the boulders from weathering processes. Though the two statements are not necessarily contradictory, they should be clarified and reconciled. Merrill (1898) and Engel and Sharp (1958) held that varnish is generally brittle and readily decomposes under moist conditions. Dorn and Oberlander (1982) reported varnish with a hardness approaching 6.5 Moh. Allen (1978) contended that varnish in the Sonoran Desert is destroyed only by sandblasting. The implications of these observations should be assessed in the context of the varnished boulder deposits on and around Yucca Mountain.

- Possibility that the boulder beds are lag accumulations which are subjected to gradual lowering without appreciable lateral displacement

  There are numerous examples of coarse residual lags which accumulate as finer matrix material is removed by both surface and subsurface erosion (Stocking, 1978; Bull et al., 1987). Oberlander (1989) described varnished boulders being lowered on hillslopes as fines are eroded. This example was from Arizona in an area receiving about 180-mm mean annual rainfall (just 30 mm or 20 percent more than that estimated for Yucca Mountain).

- Possibility that boulders below the surface are varnished

  Figure 12 of the TR suggests that the hillslope boulder beds can be thicker than the depth of just one boulder. It would be valuable to ascertain whether any of the buried blocks are varnished.

- Demonstration that the hillslope boulder deposits are unequivocally of cryogenic or periglacial origin

  Frost-weathering is proposed in the TR as the predominant mechanism for forming hillslope boulder deposits. While there is strong evidence that parts of the American southwest experienced glacial and periglacial conditions at times during the Quaternary, the paleoclimatic information for the existence of such conditions at Yucca Mountain is less than convincing. Blocky hillslope deposits such as those found on and around Yucca Mountain are not exclusively the products of frost weathering. For example, coarse talus slopes occur in many desert environments which have not been subjected to frost weathering during the Quaternary. Mechanical weathering as a result of temperature fluctuations (insolation), periodic wetting and desiccation, and salt impregnation have all been invoked to account for granular disintegration of rock in arid settings (Goudie, 1989). In this context, it is significant that Harrington and Whitney (1987: p. 970) felt that "higher accumulation rates and more alkaline composition of dust probably resulted from deflation of dry playas that persisted over great aerial (*sic*) extent and for long periods of time" near Yucca Mountain during the Pleistocene. Such dust deposits are often saline and salts are commonly an important, even pre-eminent, factor in desert weathering processes (Goudie, 1989; Watson, 1992; Cooke et al., 1993).

  Whitney and Harrington (1993) described hillslope boulders on Yucca Mountain that have been split at some time following the formation of desert varnish on their surfaces. If this phenomenon is also attributed to frost weathering, is it possible to reconcile it with the fact that the varnish must therefore have been preserved during a cool and moist climatic episode?

  In the TR it is argued that hillside boulder stripes are probably of periglacial origin. Certainly, the features appear to resemble cryogenic landforms (Prokopovich, 1987) but other possible origins cannot be summarily dismissed. For example, Melton (1965) describes linear boulder fields running normal to hillslope contours in Arizona. Similar features are common in many subtropical deserts. Oberlander (1989: p. 66) noted that "whereas alpine talus has attracted much study, desert talus has received minimal attention." The origin of the boulder stripes is probably related to preferential erosion of fines creating a lag of coarse debris in shallow ravines on the flanks of hills. The precise erosional mechanisms are diverse, so the landforms are not necessarily characteristic of a specific climatic regime. The origin of the linear boulder deposits on Yucca Mountain requires further investigation.

Overall, the paleoenvironmental history that has been proposed in the TR requires additional consideration. Most of the glacial features in northern Nye County are attributed to a late (terminal) Pleistocene age (Kleinhampl and Ziony, 1985). It seems likely that late Pleistocene climate was at least as cold and probably colder than at any other time during the Quaternary Period. The proposed antiquity of the boulder deposits indicates that they were formed during relatively warmer periods of the Quaternary. The lack of such deposits forming during the cooler portion of the Quaternary (i.e., the late Pleistocene) should be discussed.

- Demonstration that the desert varnish is representative of the age of the boulder deposits

Reneau and Raymond (1991) and Reneau et al. (1992) pointed out that the thickest varnish coatings on individual rocks are commonly in shallow depressions on the rock surface. In this TR it is stated that the thickest varnishes on individual boulders were sampled for analysis. In view of the foregoing comments regarding the possible preservation of varnish on mobile boulders, the possibility that the basal portions of thick varnish coatings predate emplacement of the boulders must be considered.

In the TR it is stated that there is a possibility that the varnish formed on the hillslope boulder deposits at some time well after their stabilization. It is argued, however, that VCR dates, which underestimate the age of the boulder deposits, would merely result in higher (and therefore conservative) estimated rates of subsequent incision. Therefore, such underestimation of the deposits ages are not incompatible with the principal goals of the study. However, if such age underestimations also occur in the case of the calibration samples, the foundation of the whole study is significantly eroded. This issue is discussed further in the following section.

5.2 STATISTICAL ANALYSES OF VARNISH CATION-RATIO DATA

The precision of the analytical procedures and the accuracy of the results require careful evaluation (Bierman and Gillespie, 1991). In their discussion of the SEM-EDS analytical methodology, Harrington and Whitney (1989: p. 968) stated that "the VCR decreases to a minimum value at some depth in the varnish and then gradually increases with increasing penetration...the VCR minima occur at, or just below, the voltage at which Mn and Fe maxima are obtained; these are the values we select to calculate a VCR for each rock." Despite these procedures, there is a possibility that inclusion of substrate could affect the KCT determinations (Reneau and Raymond, 1991). Moreover, the peer review for the Yucca Mountain rock varnish study noted that "the consistency of their results suggests that the Los Alamos investigators know by experience when the varnish is correctly averaged — without requiring an obtrusive display of substrate contamination. Nevertheless, we believe that there should be a check on the procedure" (Birkeland et al., 1989: p.7). It is unclear whether such a check has been employed in the analytical procedures adopted for the purposes of this study.

In the TR, the VCRs are calculated using the standardless semiquantitative (SSQ) program described by Harrington and Whitney (1987: p. 968). However, Harrington et al. (1991: p. 60) stated that "the inadequacy of SSQ to provide reliable Ti concentrations in the presence of Ba suggests the need for a reanalysis, using MICRO Q or SQ, of the rock varnish samples used in the calibration of the rock-varnish dating curve of Harrington and Whitney (1987)." Yet in this TR (p.42) it is stated that "the rock-varnish dating curve for Yucca Mountain (Harrington and Whitney, 1987) was calibrated using cation ratios calculated from data derived using the SSQ program. Thus, the age estimates for these colluvial boulder deposits are obtained by plotting SSQ-generated cation ratios on this dating curve..." It is unclear whether the correction for Ba content in order to determine the VCR (using [Ca + K]/[Ti + 1/3 Ba] instead of [Ca+K]/Ti) has been used to recalculate the VCRs of the calibration samples or whether it is merely adopted to bring the boulder deposit VCR data into conformity with the earlier calibration sample analyses. This confusion requires careful clarification. If the present VCR data do not correspond to those used to determine the calibration curve, the accuracy of the dating is seriously compromised. This notwithstanding, the continued use of the SSQ program despite the comments of Harrington et al. (1991) must be better justified.

Only five of the six readings obtained from the VCR analyses of individual disks from varnished boulders were employed in the calculation of the mean VCR by Harrington and Whitney (1987: p. 969); the highest VCR reading was discarded. In this TR (p. 42), it is stated that the VCR "is calculated for six overlapping sites on each disk...and averaged." However, the number of analytical sites for each geomorphic surface presented in Table 4 of the TR imply that probably data from five sites/disk are used. Not only does this discrepancy require clarification but the logic for rejecting the highest VCR value from each disk must be elucidated. If VCR data from only five sites/disk are used, the mean VCRs will be unduly low and will give an older age for the varnish than is justified.

It should be stressed that when the available data are analyzed statistically (not all pertinent data has been provided yet to the NRC), the standard deviations and the coefficients of variation for the sample populations are very large (see Table 5-1). Even using only the 5 lowest VCR readings from each disk, 8 of the 15 data sets (12 boulder deposits and 3 calibration points) have coefficients of variation greater than 20 percent.

The range in VCR readings on individual disks (5 readings), individual boulders (10 readings) and single geomorphic surfaces (30 to 170 readings) can be extremely large (see Table 5-2). Converted to age ranges using the linear calibration of Harrington and Whitney (1987), sample population VCRs represent age ranges from 1,000 to 800,000 yr (Q2b); 30,000 to over 2 million yr (Q2c); 10,000 to 640,000 yr (YME-2); and so on. Evidently, the varnishes are very heterogeneous. This is especially striking when it is considered that biased sampling of only the very heavily and darkly varnished boulders is accomplished, data from some disks with high mean VCRs are not used, and only the five lowest readings from each disk are used in the calculations. Moreover, ranges on individual disks can also be very high, for example, from 60,000 to 350,000 yr (Q2b), even though the individual analytical sites overlap.

These high ranges in VCR values and large coefficients of variation for the sample populations require careful consideration. It is particularly important to reassess the accuracy of the points on the calibration curve. The true standard deviation for unit CF is about 1.6, not the 1.0 reported in the TR, and that for Q2b is about 1.9, not the 0.53 of the TR. The respective coefficients of variation are about 26 and 33 percent. Although the raw VCR data for the Black and Red Cone calibration points have not yet been made available, the mean disk VCRs indicate a similarly high coefficient of variation. The "grand mean" for the Black Cone sample is 2.18 but the lowest mean disk VCR is 1.493. Clearly, the true age of the varnish cannot predate the age of the volcanic substrate which might be interpreted to mean that there is a 30-percent analytical error in this case.

Table 5-1. VCR and age ranges from TR data

Surface	Number Of Individual VCRs[1]	Mean VCR[2]	Sample Standard Deviation[3]	VCR Mean ±1 Standard Deviation	U[4]	Age kabp[5]	Age ±/1U[6] kabp	V[7]	SEV[8]
YME-1	70 (55)	3.1	0.5	2.6 - 3.6	3.0 - 3.2	580	530 / 630	16	1.4
YME-2	100 (80)	4.9	1.0	3.9 - 5.9	4.7 - 5.1	120	110 / 140	20	1.4
YMW-1	70 (55)	3.6	0.8	2.8 - 4.4	3.4 - 3.8	380	330 / 430	22	1.9
YMW-2	80 (40)	3.5	0.8	2.7 - 4.3	3.3 - 3.7	410	360 / 470	23	1.8
YMW-3	85 (65)	3.0	0.4	2.7 - 3.4	3.0 - 3.1	630	590 / 670	13	1.0
YMN-1	65 (40)	3.3	0.6	2.7 - 3.9	3.2 - 3.5	490	440 / 540	18	1.6
LSM-1	160 (160)	2.5	0.4	2.1 - 2.9	2.5 - 2.6	970	930 / 1020	16	0.9
SKM-1	60 (45)	3.1	0.8	2.3 - 3.9	2.9 - 3.3	580	500 / 670	26	2.4
SKM-2	30 (30)	2.7	0.2	2.5 - 2.9	2.6 - 2.9	820	770 / 860	7	1.0
SKM-3	35 (35)	2.3	0.3	2.0 - 2.64	2.2 - 2.4	1150	1070 / 1240	13	1.6
SKM-3A	60 (50)	2.8	0.7	2.1 - 3.5	2.6 - 3.0	750	660 / 850	25	2.3
BM-1	39 (40)	2.1	0.3	1.7 - 2.4	1.9 - 2.2	1370	1280 / 1470	14	1.6
CF	89	6	2	4 - 8	6 - 7	40	30 / 60	33	2.5
Q2b	109	6	2	4 - 8	4 - 5	60	40 / 70	20	1.0
Q2c	190	5	2	3 - 7	4 - 4	120	140 / 180	25	1.4

Footnotes:
1 - Number of individual VCRs used in calculations. (x) = Number of VCRs used in the TR calculations.
2 - Mean VCR (Calculated from the individual VCRs)
3 - Sample Standard Deviation (calculated using N - 1)
4 - Range of uncertainty wherein it is likely, at 95-percent CL, that the true mean will fall; Calculated as $U = M \pm t^{*}Sm$, where t is the t-statistic at the 95-percent confidence level, and $Sm = S/\sqrt{N}$
5 - Mean age in kabp from calibration curve in TR
6 - Age range about the sample population mean wherein the true mean is likely to lie at the 95 percent confidence level. Expressed as kabp.
7 - Coefficient of Variation; S/M* 100 percent
8 - Standard Error of Variation

Table 5-2. Maximum range in VCR ages from TR data

Surface	Number[1]	Average Age[2] kabp	Single Disk Age Range kabp	Single Boulder (Clast) Age Range kabp	Total Age Range kabp	M+1S[3] Age kabp	M-1S[4] Age kabp
YME-1	70	580	1060-530	800-170	1060–170	890	380
YME-2	100	120	120-20	310-10	640–10	290	50
YMW-1	70	380	630-290	300-80	990–60	750	190
YMW-2	80	410	870-450	870-260	940–120	820	210
YMW-3	85	630	680-390	1150-420	1150–260	890	450
YMN-1	65	490	1110-520	500-170	1110–170	820	290
LSM-1	160	970	780-460	1100-440	1720–440	1370	690
SKM-1	60	580	590-280	700-280	1480–100	1150	290
SKM-2	30	820	950-590	990-590	1100–590	970	690
SKM-3	35	1150	1770-1030	1770-1030	1770–650	1490	890
SKM-3A	60	750	1650-750	1650-140	1650–140	1370	410
BM-1	39	1370	1630-1270	1270-610	1860–610	1780	1060
CF	89	40	40-2	700-10	730–2	170	10
Q2b	109	60	350-60	800-30	800–1	290	10
Q2c	190	160	160-20	520-40	2090–30	490	50

Footnotes: 1 - Number of individual VCRs used in calculations

2 - Mean VCR age (Calculated from the individual VCRs) in thousands of years before present (kabp)

3 - Age = Mean + 1 Standard Deviation

4 - Age = Mean - 1 Standard Deviation

5.3 VARNISH CATION-RATIO CALIBRATION CURVE ACCURACY

The quantity and quality of the VCR data and absolute ages used to determine the calibration curve for the study are inadequate. Notwithstanding the many other criticisms of this TR, the precision and accuracy of the VCR calibration curve is of fundamental importance. If the calibration cannot be shown to be rigorous, the conversion of the VCR data to absolute ages of the deposits is invalid. Bierman et al. (1991: p. 138) stated that "if numerical cation ratio ages are generated using a calibration curve, then the accuracy and precision of cation-ratio calibration must be considered rigorously before cation-ratio ages can be compared to ages generated by other dating methods." Moreover, the group that reviewed the rock varnish studies (Birkeland et al., 1989) noted that "calibration needs to be a continuing part of the project, especially as more detailed fieldwork or discussion with other workers suggest potentially good sites." Yet, the calibration curve used in this TR is essentially that published by Harrington and Whitney in 1987, and this was based on fieldwork undertaken between 1984 and 1986 (Whitney and Harrington, 1993).

In order for the calibration curve which shows the relationship between VCR and absolute age of the varnish to be valid, three main criteria must be met. First, the VCR of the calibration samples must be accurate; second, the absolute age of the deposit associated with the varnish must be accurate; and, third, there must be an unequivocal temporal relationship between the onset of varnish formation and the age of the associated material.

Most of the foregoing comments about the accuracy of the VCR determinations also apply to the calibration sample analyses (Harrington and Whitney, 1987). Several additional points must also be raised. The number of analyses which were undertaken in order to ascertain the VCR for the calibration is not stated in this TR or by Harrington and Whitney (1987). They state merely that "the average of eight or more individual rock cation ratios per field locality" were determined. Does this refer to the number of analytical sites on disks, the number of disks, or the number of sampled clasts? The total number of analytical sites must be specified in order to assess the statistical validity of the sample data.

Bierman et al. (1991: p. 136) pointed out that "analytical uncertainties decrease as a function of the square root of the dwell time" which is the duration of the analysis at each site on each disk. They found that measurement precision increased threefold when dwell time was increased from 40 s to between 4,000 and 6,000 s. It is striking that the VCR data presented in the TR were obtained by analyses with a 150-s dwell time (p. 40) in contrast to a 100-s dwell time for the calibration sample analyses (Harrington and Whitney, 1987: p. 968). It would seem appropriate to determine calibration VCRs with at least the same, if not more, precision than of subsequent sample analysis.

It has also been pointed out (Reneau and Raymond, 1991: p. 940) that "sampling of varnish from compositionally variable substrates" may result in "increased uncertainties in the age estimates." Of the five points on the calibration curve of Harrington and Whitney (1987), two are of varnish from basaltic rock and three are of varnish from welded rhyolitic tuff. Varnishes from the two different substrates have very different VCRs (Table 4-1). Moreover, this marked distinction also occurs in the VCRs obtained from lithologically different boulders on the various geomorphic surfaces. The likelihood that the nature of the substrate has an overriding influence on VCR, superseding that of varnish age, should be very carefully considered.

5.4 ACCURATE DATING OF CALIBRATION POINTS

Accurate dating of the materials associated with the VCR calibration samples is essential. For example, Pineda et al. (1988) used age estimates based on stone-tool typology to date VCR calibration samples. However, the southern African Middle Stone Age (MSA) stone-tool typology is still being revised. Hence, while an artifact may be unequivocally attributed to MSA II, for example, different authorities may ascribe very different dates to this archaeological period. There is a danger that essentially accurate VCR data are converted to absolute ages of questionable accuracy because the calibration curves are not analytically rigorous. Major uncertainties in the calibration curves do not allow for accurate VCR dating.

The eruption ages of Black and Red Cones are well represented by K-Ar dates of fresh rock because the chemical system became closed to K and Ar mobility when the rock cooled to ambient temperatures. However, varnish developed at some indeterminate time subsequent to cooling, and thus the age of the varnish may not be well represented by the whole-rock K-Ar date. During a 1994 field trip Dr. Harrington indicated that there may be several hundred thousand years between these two events. Before K-Ar dates of lava flows can be used to represent varnish ages, the amount of time between lava cooling and varnish formation must be quantified.

5.5 URANIUM-TREND DATING TO ESTABLISH VARNISH AGE

It was pointed out in the foregoing discussion that the varnish used for the calibration of VCR data must have formed on alluvial clasts at some indeterminate time following deposition of the sediment. Moreover, it is not the clasts that have been dated but rather the accumulation of U and Th in fine-grained material within the alluvium. As such, the absolute dates are not necessarily representative of the age of either the alluvium or the desert varnish. Hence, the varnish may be much younger (Harden et al., 1988) or possibly much older than the uranium-trend age of the associated deposit. This is a common concern when dating alluvial soil horizons or the materials included within them (Watson, 1992). The implications on the purported ages of varnishes used to construct the VCR calibration curve must be very carefully considered.

In the TR, three of the five calibration points are dated using U-trend methods. Swadley et al. (1984) used these same dates to estimate the ages of Quaternary soils and alluvial deposits in the vicinity of Yucca Mountain. They noted that the dating method was experimental and "that accuracy of the absolute ages derived by this method is not known..." (Swadley et al., 1984: p. 6). Geyh and Schleicher (1990: p. 226) also question whether U-trend dates actually represent the age of the deposit. No data have been presented in the TR to demonstrate that the U-trend dates used in the calibration curve either precisely or accurately represent the age of the varnish associated with these deposits. Although Harrington et al. (1988: p. 1052) stated that the "analytical uncertainty in the K-Ar and U-series dates is minimal," the Los Alamos National Laboratory peer-review group felt that "additional calibration points should use all suitable methods" (Birkeland et al., 1989: p. 6).

5.6 LACK OF ACTUAL VARNISH CATION-RATIO DATA IN TOPICAL REPORT

One of the main technical criticisms of the TR is that true VCR data are not presented; the only data that are provided are the mean VCR figures for the 12 geomorphic surfaces that have been studied. Without the full complement of raw data to evaluate, the following concerns arise:

- It is unclear to what the data presented in Table 4 of the TR pertain

  Presumably, there are six analytical sites/disk (though it seems that data from only five of these are used in the study), two disks/boulder, and several boulders/geomorphic surface. The number of analytical sites and the number of boulders that have been analyzed should be clearly stated and the data for each should be provided.

- It is impossible to determine the variance in the VCR for each disk, each boulder, and each geomorphic surface because this information is not provided

  Though it is stated in the TR (p. 42) that the VCR "is the average of all varnish analyses for a colluvial boulder deposit," the "VCR for a colluvial boulder deposit is determined by averaging all the VCRs for all the sample boulders from that deposit." In effect, the VCR for the geomorphic surface (the deposit) is the mean of several means. This is an inappropriate method for determining the population variance and standard deviation. Bierman et al. (1991: p. 136) pointed out that "because varnish samples collected from different boulders are not identical, S_{CR} (sample standard deviation of the cation ratio) for multiple boulders on a single geomorphic surface should exceed σ_{CR} (the precision of each cation ratio determination)." Harrington and Whitney (1987) found that S_{CR} was greater than or equal to σ_{CR}. It is very likely that the standard deviation about the mean VCR for each geomorphic surface is greater than that provided for each deposit in Table 4 of the TR because the latter does not reflect the real variance in the VCR readings.

- A measure of the statistical significance of any differences (or similarities) between sample populations is not provided

  Whitney and Harrington (1993: p. 1013) and this TR (p. 40) pointed out that of about 20 sample clasts collected from each boulder deposit, only the best 8 to 10 were analyzed. It is stated that "this sample-selection procedure was used to reduce the analytical variability in varnish cation ratios for an individual deposit." But Bierman et al. (1991: p. 138) noted that if "the cation-ratio population (is) more heterogeneous...more samples from the population must be analyzed to achieve a similar σ." In this study, fewer samples have been analyzed despite evidence of significant heterogeneity. The chemical diversity of the varnishes must be statistically tested prior to making judgements concerning appropriate sample size.

  It should be noted that Bierman et al. (1991) based their calculations of uncertainty on the t-statistic. Hence, it is significant that they stated that the uncertainty of the mean VCR can be accurately predicted only if the population distribution is normal. Without recourse to the actual VCR readings from each disk and each boulder, it is impossible to assess whether the data are normally distributed. In this TR (p. 42) it is stated that the technique of Bierman et al. (1991) "is a more accurate measure of the true uncertainty of a calculated cation-ratio than the uncertainty measured as one standard deviation." However, when calculating the level of uncertainty (Bierman et al., 1991), it is essential that the arithmetic mean of all of the cation-ratio determinations is used. It is not clear if this has been done in the case of the calculations of uncertainty presented in Table 4 of the TR.

Provided that it is warranted by the nature of the sample population distribution, it would be possible to determine if there is any statistical difference in the VCRs from the various geomorphic surfaces. This could be readily accomplished using Snedecor's variance ratio test (F-test), for example, which enables comparison of a number of sample populations of different sizes.

- Calculations of uncertainty are not statistically rigorous

In the TR it is stated that the 12 dated boulder deposits appear to fall into five age groups. Two points should be raised. First, the population of each of these groups is too small for such a subdivision to be statistically valid. Second, and more importantly, using even the standard deviations provided in Table 4 of the TR (which are likely to be too small given the shortcomings in the statistical procedures), 11 of the 12 boulder deposit ages $\pm 1\sigma$ fall within a continuum. This is in the range of about 1,100 to 300 kabp. It is true that the VCR data for all of the Yucca Mountain boulder deposits (with the exception of YME-2) overlap at about 700 to 600 kabp when each is plotted within a range of $\pm 1\sigma$. The five deposits from Skull Mountain and Little Skull Mountain show a similar overlap close to 900 kabp. This phenomenon should be carefully addressed.

The data presented in Table 4 of the TR show that all Yucca Mountain deposits are younger than 760 kabp and all other sampled deposits are older than 800 kabp. It is essential to question whether this is a reasonable phenomenon. It is difficult to envisage how hillslope deposits on neighboring mountains would have discretely different ages. A plausible explanation is that the differences in the lithology of the boulder deposits have influenced the VCR determinations (Reneau and Raymond, 1991). On Yucca Mountain, the boulders are composed of welded rhyolite tuff and on the other hillslopes they are basalt blocks.

6 SUMMARY

There are several key issues concerning the TR on evidence of extreme erosion during the Quaternary at Yucca Mountain which have not been adequately addressed.

- It may not be valid to base estimates of average erosion and denudation rates on the dating of stable surfaces. The inception of erosional incision of a landscape is not necessarily at the same time as the stabilization of the adjacent land surface. If the erosional features are considerably younger, the rate of their formation would be commensurately higher.

- It is not appropriate to rely on only one dating method, especially one which is essentially experimental and largely untested. Other dating techniques should be used for corroboration of the VCR dates.

- It is unproven whether the VCR data are from geomorphically stable surfaces. In addition, the proposed origin of the boulder deposits is dubious. It is argued here that during the late Pleistocene, it was not cold enough at Yucca Mountain to initiate frost weathering. Based on paleoclimatic information from many other areas, it is unlikely that temperatures colder than those at the LGM occurred earlier in the Pleistocene. Therefore, an alternative model of colluvial boulder production seems necessary.

- Methods for determining VCRs require further validation.

- VCR data presented in this TR are incomplete. Data from individual analytical sites, disks, and boulders should be provided. Moreover, rigorous testing must be undertaken to assess whether the results obtained from these sample analyses are statistically significant.

- Calibrations used to convert VCRs to absolute dates are inadequate and possibly erroneous.

- Determination of long-term erosion rates spanning intervals of 100 ka is probably inappropriate since major erosional episodes may have occurred over time spans of 10 ka or less and are separated by periods of low geomorphic activity. By presenting data averaged over periods of both low and high levels of geomorphic activity, the significance and intensity of the erosional phases is seriously diluted. In this study, it seems to be lost.

- Paleoenvironmental implications of this study are not adequately discussed. In some respects, the conclusions contradict those reached by other researchers working in the same geographical area. The apparent inconsistencies should be reconciled or the broader implications of the suggested modifications to the region's paleoenvironmental record should be thoroughly evaluated.

- Discussion of the stratigraphic and geomorphic significance of the alluvial sediments in Fortymile Wash requires elaboration. The two scenarios representing different possible sedimentological histories for the deposits are markedly disparate. The implications of each are profoundly different and possibly incongruous with the suggested erosional history of the area. Further clarification is warranted.

- Results of this study do not in themselves adequately address the question of likely future erosional phenomena. Issues such as man's likely impact on geomorphic processes and the critical question of current and future erosion potential are of fundamental significance.

- Previous concerns expressed by NRC/CNWRA (CNWRA, 1992) have apparently been either incompletely addressed or not been considered at all.

Appendix C is a list of 21 questions/concerns which were developed by the CNWRA and the NRC. These concerns were transmitted to the DOE prior to the NRC/CNWRA visit to Yucca Mountain. The DOE structured its presentations during the 2-day field trip to address the concerns.

7 REFERENCES

Allen, C.C. 1978. Desert varnish of the Sonoran Desert — optical and electron probe analysis. *Journal of Geology* 86: 743–752.

Bierman, P.R., and A.R. Gillespie. 1991. Accuracy of rock-varnish chemical analyses: implications for cation-ratio dating. *Geology* 19: 196–199.

Bierman, P.R., and A.R. Gillespie. 1994. Evidence suggesting that methods of rock-varnish cation-ratio dating are neither comparable nor consistently reliable. *Quaternary Research* 41: 82–90.

Bierman, P.R., A.R. Gillespie, and S. Kuehner. 1991. Precision of rock-varnish chemical analyses and cation-ratio ages. *Geology* 19: 135–138.

Birkeland, P.W. 1992. Quaternary soil chronosequences in various environments — extremely arid to humid tropical. *Weathering, Soils, and Paleosols*. I.P. Martini and W. Chesworth, eds. Amsterdam, Elsevier: 261–281.

Birkeland, P.W., T.M. Oberlander, and J.W. Hawley. 1989. *Peer Review Report on Rock-Varnish Studies Within the Yucca Mountain Project*. Los Alamos, NM: Los Alamos National Laboratory, Earth and Space Sciences Division, Geology and Geochemistry Group (ESS-1): 8.

Bishop, P. 1985. Southeast Australian late Mesozoic and Cenozoic denudation rates: a test for late Tertiary increases in continental denudation. *Geology* 13: 479–482.

Bish, D.L., and S.J. Chipera. 1989. *Revised Mineralogic Summary of Yucca Mountain, Nevada*. Los Alamos National Laboratory Report LA-11497-MS. Los Alamos, NM: Los Alamos National Laboratory.

Broxton, D.E., R.G. Warren, F.M. Byers, Jr., and R.B. Scott. 1989. Chemical and mineralogic trends within the Timber Mountain-Oasis Valley caldera complex, Nevada: Evidence for multiple cycles of chemical evolution in a long-lived silicic magma system. *Journal of Geophysical Research* 94(B5): 5,961–5,985.

Bull, P.A., A.S. Goudie, D. Price Williams, and A. Watson. 1987. Colluvium: a scanning electron microscope study of a neglected sediment type. *Clastic Particles*. J.R. Marshall (eds.). New York, NY: Van Nostrand Reinhold: 16–35.

Center for Nuclear Waste Regulatory Analyses. 1992. *Comments on DOE Erosion Topical Report Outline*. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses: 13p.

Cooke, R., A. Warren, and A. Goudie. 1993. *Desert Geomorphology*. London, England: UCL: 526.

Crowe, B.M., K.H. Wohletz, D.T. Vaniman, E. Gladney, and N. Bower. 1986. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations*. Los Alamos National Laboratory Report LA-9325-MS, Vol. II. Los Alamos, NM: Los Alamos National Laboratory.

Crowe, B., R. Morley, S. Wells, J. Geissman, E. McDonald, L. McFadden, F. Perry, M. Murrell, J. Poths, and S. Forman. 1992. The Lathrop Wells volcanic center: Status of field and geochronology studies. *Proceedings of the Third International High Level Radioactive Waste Management Conference*. La Grange Park, IL: American Nuclear Society: 1,997-2,013.

Dardis, G.F. 1990. Late Holocene erosion and colluvium deposition in Swaziland. *Geology* 18: 934-937.

Dorn, R.I. 1983. Cation-ratio dating: a new rock varnish age-determination technique. *Quaternary Research* 20: 49-73.

Dorn, R.I. 1984. Cause and implications of rock varnish microchemical laminations. *Nature* 310: 767-770.

Dorn, R.I. 1990. Cation-ratio dating of rock varnish: A geographical perspective. *Progress in Physical Geography* 13: 559-596.

Dorn, R.I. 1992. Comment on "Accuracy of rock-varnish chemical analyses: Implications for cation-ratio dating." *Geology* 20: 470-471.

Dorn, R.I., and D.H. Krinsley. 1991. Cation-leaching sites in rock varnish. *Geology* 19: 1,077-1,080.

Dorn, R. I., and F.M. Phillips. 1991. Surface exposure dating: review and critical evaluation. *Physical Geography* 12: 303-333.

Dorn, R.I., and T.M. Oberlander. 1982. Rock varnish. *Progress in Physical Geography* 6: 317-367.

Dorn, R.I., D. Bamforth, T.A. Cahill, J.C. Dohrenwendt, B.D. Turrin, D.J. Donahue, A.J.T. Jull, A. Long, M.E. Macko, E.B. Weil, D.H. Whitney, and T.H. Zabel. 1986. Cation-ratio and accelerator radiocarbon dating of rock varnish on Mojave artifacts and landforms. *Science* 231: 830-833.

Dorn, R.I., M.J. DeNiro, and H.O. Ajie. 1987. Isotopic evidence for climatic influence on alluvial-fan development in Death Valley. *Geology* 15: 108-110.

Dorn, R.I., A.J.T. Jull, D.J. Donahue, T.W. Linick, and L.J. Toolin. 1989. Accelerator mass spectrometry radiocarbon dating of rock varnish. *Geological Society of America Bulletin* 101: 1,363-1,372.

Engel, C.G., and R. Sharp. 1958. Chemical data on desert varnish. *Bulletin of the Geological Society of America* 69: 487-518.

Geyh, M.A., and H. Schleicher. 1990. *Absolute Age Determination*. New York, NY: Springer Verlag.

Gile, L.H. 1966. Cambic and certain non-cambic horizons in desert soils of southern New Mexico. *Proceedings of the Soil Science Society of America* 30: 773-781.

Gile, L.H. 1975. Holocene soils and soil-geomorphic relations in an arid region of southern New Mexico. *Quaternary Research* 5: 321-360.

Gile, L.H. 1977. Holocene soils and soil-geomorphic relations in a semiarid region of southern New Mexico. *Quaternary Research* 7: 112-132.

Gile, L.H., and R.B. Grossman. 1968. Morphology of the argillic horizon in desert soils of southern New Mexico. *Soil Science* 106: 6-15.

Goudie, A.S. 1989. Weathering processes. *Arid Zone Geomorphology*. D.S.G. Thomas, ed. London, England: Belhaven: 11-24.

Hall, G.F. 1983. Pedology and geomorphology. *Pedogenesis and Soil Taxonomy. I. Concepts and interactions*. L.P. Wilding, N.E. Smeck, and G.F. Hall, eds. Amsterdam, The Netherlands: Elsevier: 117-140.

Harden, J.W., M.C. Reheis, J.M. Sowers, and J.L. Slate. 1988. Comment on "Scanning electron microscope method for rock-varnish dating." *Geology* 16: 1,051.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Harrington, C.D., D.P. Dethier, and J.W. Whitney. 1988. Reply to comment on "Scanning electron microscope method for rock-varnish dating." *Geology* 16: 1,051-1,052.

Harrington, C.D., D.J. Krier, R. Raymond, and S.L. Reneau. 1991. Barium concentration in rock varnish: implications for calibrated rock varnish dating curves. *Scanning Microscopy* 5: 55-62.

Hooke, R.L., and R.I. Dorn. 1992. Segmentation of alluvial fans in Death Valley, California: new insights from surface exposure dating and laboratory modelling. *Earth Surface Processes and Landforms* 17: 557-574.

Hoover, D.L. 1989. *Preliminary Description of Quaternary and Late Pleistocene Surficial Deposits at Yucca Mountain and Vicinity, Nye County, Nevada.* USGS Open File Report 89-359. Reston, VA: U.S. Geological Survey: 45.

Kearey, P. 1993. *The Encyclopedia of the Solid Earth Sciences*. Oxford, England: Blackwell Scientific: 713 pp.

Kleinhampl, F.J., and J.I. Ziony. 1985. *Geology of Northern Nye County, Nevada.* Nevada Bureau of Mines & Geology Bulletin 99-A. Reno, NV: University of Nevada.

Knauss, K.G., and T.-L. Ku. 1980. Desert varnish: potential for age dating via uranium-series isotopes. *Journal of Geology* 88: 95-100.

Krinsley, D.H., R.I. Dorn, and S. Anderson. 1990. Factors that may interfere with the dating of rock varnish. *Physical Geography* 11: 97-119.

Krumbein, W.E., and K. Jens. 1981. Biogenic rock varnishes of the Negev Desert (Israel): an ecological study of iron and manganese transformation by cyanobacteria and fungi. *Oecologia* 50: 25-38.

Luo, S., and T.-L Ku. 1991. U-series isochron dating: a generalized method employing total-sample dissolution. *Geochimica et Cosmochimica Acta* 55: 555-564.

Melton, M.A. 1965. Debris-covered hillslopes of the southern Arizona desert — consideration of their stability and sediment contribution. *Journal of Geology* 73: 715-729.

Merrill, G.P. 1898. Desert varnish. *Bulletin of the United States Geological Survey* 150: 389-391.

Oberlander, T.M. 1989. Slope and pediment systems. *Arid Zone Geomorphology*. D.S.G. Thomas, ed. London, England: Belhaven: 56-84.

Perry, R.S., and J.B. Adams. 1978. Desert varnish: evidence for cyclic deposition of manganese. *Nature* 276: 489-491.

Pineda, C.A., M. Peisach, and L. Jacobson. 1988. Ion beam analysis for the determination of cation ratios as a means of dating southern African rock varnishes. *Nuclear Instruments and Methods in Physics Research* B35: 463-466.

Potter, R.M., and G.R. Rossman. 1979. The manganese- and iron-oxide mineralogy of desert varnish. *Chemical Geology* 25: 79-94.

Prokopovich, N.P. 1987. Rock stripes on Sierra Nevada foothills. *California Geology* 40: 27-30.

Reneau, S.L., and R. Raymond. 1991. Cation-ratio dating of rock varnish: why does it work? *Geology* 19: 937-940.

Reneau, S.L., W.E. Dietrich, R.I. Dorn, C.R. Berger, and M. Rubin. 1986. Geomorphic and paleoclimatic implications of latest Pleistocene radiocarbon dates from colluvium-mantled hollows, California. *Geology* 14: 655-658.

Reneau, S.L., R. Raymond, and C.D. Harrington. 1992. Elemental relationships in rock varnish stratigraphic layers, Cima volcanic field, California: Implications for varnish development and the interpretation of varnish chemistry. *American Journal of Science* 292: 684-723.

Rosholt, J.N., C.A. Bush, W.J. Carr, D.L. Hoover, W.C. Swadley, and J.R. Dooley, Jr. 1985. *Uranium-Trend Dating of Quaternary Deposits in the Nevada Test Site Area, Nevada and California*. U.S. Geological Survey Open-File Report 85-540. Reston, VA: U.S. Geological Survey.

Scientific Application International Corporation. 1992. *Report on Early Site Suitability Evaluation of the Potential Repository Site at Yucca Mountain, Nevada*. Technical and Management Support Services DE-AC08-87NV10576. Las Vegas, NV: Scientific Application International Corporation: 2-72.

Schlesinger, W.H. 1985. The formation of caliche in soils of the Mojave Desert, California. *Geochimica et Cosmochimica Acta* 49: 57-66.

Sinnock, S., and R.G. Easterling. 1983. *Empirically Determined Uncertainty in Potassium-Argon Ages for Plio-Pleistocene Basalts from Crater Flat, Nye County, Nevada.* SAND 82-2441. Albuquerque, NM: Sandia National Laboratory.

Spalding, W.G. 1985. *Vegetation and Climates of the Last 45,000 Years in the Vinicity of the Nevada Test Site, South-Central Nevada.* U.S. Geological Survey Professional Paper 1329. Reston, VA: U.S. Geological Survey.

Stocking, M.A. 1978. Interpretation of stone-lines. *South African Geographical Journal* 60: 121–134.

Summerfield, M.A. 1991. *Global Geomorphology.* Harlow, England: Longman Scientific and Technical.

Swadley, W.C., D.L. Hoover, and J.N. Rosholt. 1984. *Preliminary Report on Late Cenozoic Faulting and Stratigraphy in the Vicinity of Yucca Mountain, Nye County, Nevada.* U.S. Geologica Survey Open File Report 84–788. Reston, VA: U.S. Geological Survey: 42.

Tardy, Y. 1992. Diversity and terminology of lateritic profiles. *Weathering, Soils and Paleosols,* I.P. Martini and W. Chesworth, eds. Amsterdam, The Netherlands: Elsevier: 379–405.

Tardy, Y., and C. Roquin. 1992. Geochemistry and evolution of lateritic landscapes. *Weathering, Soils and Paleosols.* I.P. Martini and W. Chesworth, eds. Amsterdam, The Netherlands: Elsevier: 407–443.

Turrin, B.D., D. Champion, and R.J. Fleck. 1991. $^{40}Ar/^{39}Ar$ age of the Lathrop Wells Volcanic Center, Yucca Mountain, Nevada. *Science* 253: 654–657.

U.S. Department of Energy. 1988. *Site Characterization Plan: Yucca Mountain Site, Nevada Research and Development Area, Nevada.* DOE/RW-0199. Washington, DC: U.S. Department of Energy: Office of Civilian Radioactive Waste Management. 9 Volumes.

U.S. Department of Energy. 1991. *General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories.* Title 10, Energy, Part 960 (10 CFR Part 960). Washington, DC: U.S. Government Printing Office.

U.S. Department of Energy. 1993. *Topical Report: Evaluation of the Potentially Adverse Condition "Evidence of Extreme Erosion During the Quaternary Period at Yucca Mountain, Nevada.* YMP/92-41-TPR. Washington, DC: U.S. Government Printing Office.

U.S. Environmental Protection Agency. 1991. *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes.* Title 40, Protection of Environment, Part 191 (40 CFR Part 191). Washington, DC: U.S. Government Printing Office.

U.S. Nuclear Regulatory Commission. 1983. *Staff Analysis of Public Comments on Proposed Rule 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories.* NUREG-0804. Washington, DC: Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

U.S. Nuclear Regulatory Commission. 1993. *Disposal of High-Level Radioactive Wastes in Geologic Repositories.* Title 10, Energy, Part 60 (10 CFR Part 60). Washington, DC: U.S. Government Printing Office.

Vaniman, D.T., B.M. Crowe, and E.S. Gladney. 1982. Petrology and geochemistry of Hawaiite lavas from Crater Flat, Nevada. *Contributions to Mineralogy and Petrology* 80: 341-357.

Watson, A. 1989. Desert crusts and rock varnish. *Arid Zone Geomorphology.* D.S.G. Thomas, ed. London, England: Belhaven: 25-55.

Watson, A. 1992. Desert soils. *Weathering, Soils and Paleosols.* I.P. Martini and W. Chesworth, eds. Amsterdam, The Netherlands: Elsevier: 225-260.

Whitney, J.W., and C.D. Harrington. 1993. Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada. *Geological Society of America Bulletin* 105: 1,008-1,018.

Zreda, M.G., F.M. Phillips, P.W. Kubik, P. Sharma, and D. Elmore. 1993. Cosmogenic ^{36}Cl dating of a young basaltic eruption complex, Lathrop Wells, Nevada. *Geology* 21: 57-60.

Appendix A

POINTS PERTAINING TO SPECIFIC ITEMS IN THE TEXT OF THE DOE TOPICAL REPORT "EVALUATION OF THE POTENTIALLY ADVERSE CONDITION 'EVIDENCE OF EXTREME EROSION DURING THE QUATERNARY PERIOD' AT YUCCA MOUNTAIN, NEVADA"

This Appendix contains a collection of comments on the TR which are organized on a page-by-page basis. The main topic headers from the TR are identified and the appropriate location of each item commented upon is noted.

Abstract (p. i); Executive Summary (p. viii); and 2.2 Regulatory Evaluation of Potentially Adverse Condition, "Evidence of Extreme Erosion during the Quaternary" (p. 2).

The precise definition of the term *extreme erosion* is an unnecessary exercise in semantics. The key issue is the likelihood of the repository being compromised. Moreover, NUREG-0804 (NRC, 1983) is quoted as stating that the term refers "to the occurrence of substantial changes in landforms (as a result of erosion) over relatively short intervals of time." The emphasis here is on the duration of the geomorphic event. This is significant since the estimates provided by this study are based on periods of several hundred ka and therefore encompass major variations in environmental conditions and, hence, also in geomorphic processes.

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

p. 3 The statement that "DOE believes that the more recent geologic past is a better indicator of possible future activity than the distant geologic past,..."does not undermine the NRC request to evaluate the evidence of extreme erosion for the entire Quaternary Period. The NRC is interested in finding out if any erosive process operating within the geologic setting in the Quaternary Period is significant enough to warrant its consideration as a potentially adverse condition which might affect the waste isolation capabilities of the proposed repository.

p. 4 The intended meaning of "more recent geologic past" is not clear.

The data which have been gathered "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." This time extent is not sufficient, particularly in light of the potential uncertainty associated with the cation-ratio dating process. The NRC suggests that the Quaternary Period be considered as covering 2 Ma, thus, some additional evidence for the more than 0.6 Ma not covered by the DOE work in the TR should be provided.

It is debatable whether or not the boulder deposits are dated within the stated time interval.

It is stated that the calculated erosion rates are "based on rock varnish exposure ages of colluvial boulder fields on hillslopes." The stability of the deposits must be carefully proven.

2.3 Regulatory Evaluation Conclusion

p. 4 Long-term average hillslope erosion rates are not consistent with the NRC definition of "extreme erosion" which is "substantial changes in landforms over short periods of time."

pp. 5-6 The suggestion that the VCR dates pertain to "the minimum age of the boulder deposit" is valid only if the deposits are stable and the suppositions referring to their formation are proven true.

3.0 TECHNICAL EVALUATION

3.1 Introduction

p. 7 The purpose of this "technical evaluation" refers only to the dating of hillslope boulder deposits within and adjacent to Yucca Mountain. The NRC requirement is to evaluate the evidence of extreme erosion during the Quaternary Period within the geologic setting. The geologic setting is not defined in this TR.

The evaluation references published data and extant literature. In order to conduct a thorough review of such an important topic, the basic data used to calculate the VCR ages of the boulder deposits should be included as an Appendix. It has proven difficult to acquire all the original data which established the critical age calibration curves. All applicable data is either not in the Yucca Mountain Site Characterization Project database or in the possession of the NRC as of the date of submittal of this document.

3.2 Evaluation of Degradation Rates Around the World

p. 7 It is essential to distinguish between denudation and erosion. While the two terms are often used interchangeably, it would be valuable here to differentiate between regional denudation of hillslopes (surface lowering) and more localized erosional incision of canyons and washes. The issue of backwearing (or scarp retreat) is not addressed in any detail in this report.

p. 8 It would be preferable to use metric units (precipitation is quoted in inches).

It is stated that "an unseen factor in erosion rates is time" but by definition the rate is expressed in a unit of time. By quoting mean erosion rates for very long time periods, however, the consequences of significant fluctuations in rates may be lost.

Factors influencing rates of denudation and erosion such as local relief are not adequately addressed here (see Summerfield, 1991: pp. 391-392).

p. 8 The TR states "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,... ." This seems to preclude consideration and evaluation of just the types of events which the NRC has defined as extreme erosion, that is, substantial changes of landforms in a relatively **short** interval of time.

The TR states "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." Certainly any area that had a long-term average erosion rate of 2 cm/ka could be said to be experiencing "extreme erosion" if the erosion rate approached 15 cm/ka for short intervals of time.

pp. 9, 10, and 11 See Tables 2 and 3. "Degradation Rate" should perhaps read "Denudation Rate." On p. 10, "1.18-38.9 cm/ka" seems misplaced.

3.3 Yucca Mountain Erosion Rate Assessment

p. 12 Although the present climate is arid to semi-arid, past wetter climates may have resulted in 250-350 mm/a rainfall at Yucca Mountain (Spaulding, 1985). This is within the rainfall range which typically produces maximum erosion rates (see p. 8 of the TR). Hence, although the climatic comparisons are based on present climatic conditions at Yucca Mountain, past conditions should also be considered.

Average long-term rates, while interesting, do not describe the likelihood or nature of "extreme erosion" which are substantial changes in landforms over a relatively short time interval.

The low erosion rate described in the TR acknowledges occurrence during the middle and late Quaternary. The erosion rates during the early Quaternary should be discussed as well.

The phrase "using some Quaternary dating technique" needs reworking to include a description of appropriate techniques.

p. 13 The erosion of the topographic highs between the boulder deposits which occupied the topographic lows is not discussed. The rate of erosion might be greater reducing the high elevations between the lows than on subsequent erosion between the relict boulder-filled low areas.

Proof that the boulder deposits are colluvial remnants is essential.

It is essential to prove that the boulder beds are stable, that they are not lag deposits, and that incision commenced about the same time as the deposit is purported to have become stable. For the long-term erosion rates that are presented here to be valid, they should be equated with erosional episodes rather than net incision over an arbitrary interval of time (i.e., the period since stabilization of the boulder beds).

Discussion of late Quaternary erosion is noticeably absent.

3.3.1.1 Geologic and Climatic Setting of Yucca Mountain

p. 14 "Paintbrush Tuff outcrops..." should read "Paintbrush Tuff crops out. Bedrock outcrops...."

p. 17 Pediment might be a better choice of terms than "piedmont."

The assumption that varnish forms on surfaces "as soon as they become stabilized and are no longer moved..." must be proven. The varnish may form on boulders after exhumation rather than after deposition, or at some period of time after the surface is exposed.

The resistance to weathering of the "fine-grained volcanic rocks" is a very important factor. It should be more thoroughly discussed. There are more than one type of fine-grained volcanic rocks at YMR.

p. 20 The locations of sampling points should be mapped and presented in more detail than this figure can show.

p. 21 The origin of the colluvium underlying the boulder deposits requires further discussion.

par. 2 For "resistent" read "resistant."

The various possible origins of the different boulder deposits should be discussed. Can differences in the character of frost weathering account for these variations?

p. 22 Evidence of "preservation of middle Pleistocene colluvium and the lack of erosion scars on hillsides" is not provided.

The erosion of about 5 cm of surficial material from Jake Ridge due to one storm should be considered as a type of extreme erosion in the study area. The likelihood of area wide recurrence should be evaluated for importance to potential future erosion at Yucca Mountain.

The "Jake Ridge debris-flow event" does not provide evidence that "hillslope stripping occurs primarily during warm, dry climatic conditions," or "that hillslope stripping occurs by debris flow activity." These statements are based on observations of one event. Further monitoring is required to validate these conclusions.

3.3.1.3 Distribution of Quaternary Deposits Around Yucca Mountain

p. 24 For "lower Quaternary" read "early Quaternary" and for "upper Quaternary" read "late Quaternary."

p. 24 and Figure 7, p. 26 Swadley et al. (1984) did not map colluvial deposits.

The ages of the "tilted blocks" has not been confirmed.

The statements that "deposits of late Quaternary age are chiefly confined to present stream valleys" and that "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" require validation. More field evidence is needed to support these statements, if possible, to demonstrate the age of the colluvium on the hillslopes.

p. 25 More evidence is needed to verify the statement that "weathering processes that produced large quantities of bouldery debris in the early and mid Quaternary have had a lower weathering efficiency during the late Quaternary."

Incision rates are not necessarily related to tectonics or climatic change exclusively. The discussion here is very weak. It is possible for headwall retreat to occur with very little change in local base level.

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

p. 27 The statement that "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" needs careful explanation. What evidence is there for dark varnishes being old? If it can be shown that they are old, what is the rate of darkening? Moreover, in this context, what are "relatively long periods of time?"

The calcium carbonate deposits are datable. Such dates could be used to corroborate the VCR dates.

It is stated that "no modern equivalents of the well-varnished colluvial boulder deposits are observed on southern Nevada hillslopes." But what is the evidence for modernity? This is especially pertinent since no proof is provided to show that the dark varnishes are old.

"Rigorous climatic conditions" should be defined and discussed.

p. 28 Any evidence to suggest that "freeze thaw cycles" were "of long duration...during glacial periods in the early-to-middle Quaternary" should be presented.

The observation that "If winter precipitation amounts were not significantly higher than present, then the temperature difference would be closer to 7 °C" needs clarification and explanation.

It is stated that "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," but there is no unequivocal evidence to support the contention that varnished boulders are old other than the fact that the varnish is dark.

pp. 28-29 The suggestion that early- and mid- Quaternary climates were colder than those of the late Pleistocene requires careful evaluation.

The assumption that the boulder deposits are frost-weathering phenomena should be evaluated. Many other desert weathering processes can create boulder-sized talus (Goudie, 1989; Cooke et al., 1993).

p. 29 Evidence of lacustrine sedimentation may provide evidence of a more humid mid-Quaternary climate but it does not support the assumption that the climate may also have been colder than the late Pleistocene.

pp. 29-30 The Quaternary paleoenvironmental model for southern Nevada presented here is highly speculative. No accurate dating is provided and environmental data are scant.

p. 30 It is not true that "conditions both colder and wetter than present" are "essential to produce the large boulders that form all colluvial boulder deposits." Other arid zone weathering phenomena such as salt wedging could reasonably be involved.

The phrase "if surface relief increases downslope" needs rewording.

The concept of "stranded" boulder deposits is valid only if these are formerly mobile flows rather than essentially immobile lag accumulations. This possibility requires further consideration.

The absence of boulder deposits from lower hillslopes warrants further investigation. Perhaps they are buried beneath colluvial mantles on the lower slopes or hillslope processes are fundamentally different on adjacent components of the slopes.

Evidence of calcium carbonate accumulation in soils requires further discussion and referencing. The proposed accumulation rates might be based on present rates of atmospheric fallout and the present chemistry of the fallout. It is possible that past rates of fallout and its chemistry have differed from those of today.

p. 31 The colluvial mantle may be weathered and some of this material may be colluviated, weathered bedrock (eluvium).

It may not be valid to use long-term erosion rates to evaluate likely rates over the next 10 ka as required in the NRC and EPA regulations.

3.3.2 Dating Methodology

p. 31 The logic for using only one dating technique is invalid. Other techniques may not be as useful for dating the whole time interval in question but they are nonetheless acceptable for specific portions of the Quaternary Period. Corroborating evidence for the VCR dating procedure is essential. Moreover, it is critical to validate the dating of the calibration samples using a variety of procedures.

3.3.2.1 Cation Ratio Dating of Yucca Mountain Hillslope Deposits

p. 32 It is stated that "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 boulders." The likely environmental controls on this should be discussed. The possibility for varnish being preserved on moving boulders is a general point that should be discussed in detail (cf. calibration curve).

3.3.2.1.1 Criteria for Selection of Dating Method

p. 32 - a (2) The period of stabilization is speculative.

p. 32 - a (3) This is not valid if the boulders are a lag deposit.

pp. 32-33 These other dating methods should be used to determine the ages of associated materials and thereby corroborate the VCR dates. This has been undertaken for the calibration samples and it should be done elsewhere. It is unwise to dismiss the use of these techniques in the TR but still use them for calibration purposes.

p. 34 - c It has also been stated that it is inappropriate to use VCR dating techniques on varnishes with a variety of substrate lithologies (e.g., Reneau and Raymond, 1991).

p. 34 -e Short-term rates (calculated for period of less than 100 ka) may be most valid for prediction of rates over the next 10 ka.

p. 34 - f The same criticism could be validly leveled against VCR dating techniques. It is not proven here that old varnished surfaces are destroyed by the initial weathering and subsequent erosion processes that are purported to have formed the boulder deposits.

p. 34 - 1 This model requires validation. Is it possible that the boulders were exhumed from the flanks of the hillsides?

pp. 34-35 - 2 This is only valid if the undersides of the boulders are not varnished. This needs to be tested.

p. 35 - 3 "This soft and easily eroded rock varnish" is subsequently stated to "inhibit weathering" (p. 45 - 2). This requires clarification.

p. 35 Without clearly stating the criteria used for discrimination, the "culling" of samples from 20 to 8–10 before analysis is questionable. Heterogeneous varnish deposits require **more** analyses rather than fewer in order for the analyses to be statistically rigorous (Bierman et al., 1991: p. 138).

The rejection of "anomalous" data also requires careful explanation. What criteria are used to ascertain whether the data are anomalous? Are the anomalies accounted for in estimates of the precision and accuracy of the technique, or the statistical significance of the data?

Again, the validity of dating only one component of the landscape using only one dating technique is suspect.

3.3.2.1.2 Calibration of the Cation Dating Technique

p. 36 The dating of the calibration samples assumes that the varnishes are as old as the dated materials. This is not proven and, therefore, the validity of the calibration curve is dubious.

It should be demonstrated that the Uranium-trend dates provide accurate estimates of the ages of the varnish. The soils from which the dated sediments were obtained could be much younger than the varnish. The opposite may also apply. These data must be corroborated.

The calibration of the curve with Uranium-trend dates only extends to 255 ± 15 kabp, not 500 kabp.

Rosholt et al. (1985) show that ash from Lathrup Wells Volcano (100 ± 50 ka) is interbedded with the uppermost Q2b alluvium which is dated at 255 ± 15 kabp in the TR. This contradicts the last sentence on p. 36.

3.3.2.1.3 Sampling Methods

p. 38 The concept of possible varnish modification is introduced here but there is no further elaboration.

pp. 38 and 40 All of these criteria appear to stress varnish homogeneity but is this the case? If so, why are the original 20 samples culled? It is essential to provide all of the VCR analytical data so that it is possible to assess whether the deposits do indeed have homogeneous desert varnish coatings.

p. 38 Dark varnish may be Mn-rich, but no data are presented in the TR to support this contention. Even if they are rich in Mn, the effect, if any, on subsequent VCR analyses has not been discussed throughly.

p. 40 Discuss the likely impact of sampling varnishes with lithologically different substrates (e.g., Reneau and Raymond, 1991).

3.3.2.1.5 Sample Analysis

p. 40 Count time is a meaningless parameter value unless count rates/total counts are provided.

p. 42 It is not made clear how many analytical sites/disk or disks/boulder or boulders/deposit are analyzed. This is essential in order to obtain a clear perspective on the representativeness of the sample data.

By averaging the VCR data for each boulder and then averaging all the mean VCRs for the boulders to determine the mean VCR of the deposit, significant statistical error is introduced. Such data cannot be accepted as statistically valid.

3.3.2.1.6 Calculation of Uncertainties for Cation Ratios

p. 42 It is unclear what VCR data are used in the calculations of uncertainties. The raw data from individual analytical sites should be used (Bierman et al., 1991). If mean data are used (or if the data are culled from 6 analytical sites/disk to 5), the calculations are probably invalid.

Data being used to establish the calibration curve should be presented. Most of the boulder deposit VCRs fall close to those for just two calibration samples (Red Cone and Black Cone).

3.3.2.2 Age Estimates of Varnished Boulder Deposits

p. 43 The reasons why the oldest dated deposits on Yucca Mountain are on the steepest slopes should be explained. Moreover, it may not be reasonable to assume that the freeze-thaw processes that ostensibly created the boulders have not had any subsequent impact on the deposits for nearly 750 ka. This would negate the influence of most major glacial epochs of the Quaternary that have been recognized in western North America and elsewhere.

The subdivision of the various hillslope boulder deposits into five temporal groups cannot be statistically justified. The number of sampled deposits (12), and the number of examples in each age group (3 or fewer) render the grouping statistically insignificant. The assumption that boulder deposits formed episodically during the Quaternary cannot be proven since "too few deposits have been dated to demonstrate it statistically" (p. 43).

p. 45 Though dark varnish is often considered to be old, substrate properties commonly influence varnish coloration (Watson, 1989). Again, rates of varnish darkening are not discussed in this report so there is a major flaw in much of the reasoning used in the construction of the proposed paleoenvironmental chronology.

3.3.2.3 Preservation of Colluvial Boulder Deposits on Yucca Mountain Area Hillslopes

p. 45 - 2 It is stated earlier in the report that the varnish is "soft and easily eroded" (p. 35 - 3), but not how it inhibits weathering.

p. 45 It is possible that the different rock types account for the apparent discrimination in VCR ages. This possibility has been raised by Reneau and Raymond (1991).

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

p. 46 It is stated that "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." However, the varnish might be considerably younger and, more significantly, the boulders may be lag deposits which have been lowered onto the hillside. Furthermore, calculations of incision rates do not take into account the fact that erosion adjacent to the purportedly stable boulder deposits may have commenced long after they were stabilized. If this were the case, the calculated erosion rates would be unrepresentatively low.

For "lenticular cross-section shape" and "slight topographic highs" read "low ridges with a concave cross-section."

p. 48, Table 5 Again, the "long-term average hillslope degradation rate" probably misrepresents the erosion rates during periods of hillslope incision. These periods may have lasted for 10 ka or more (for example, the whole of the Holocene). Hence, they are by no means *short-term* phenomena. The geomorphic impact of such episodes may be considerable but it is all but lost if the erosion rate is calculated in terms of average incision over 500 ka or more. The key issue is whether mean geomorphic conditions for the past 500 ka are likely to be representative of conditions over the next 10 ka. Geomorphic events during the late Pleistocene or perhaps the Holocene are perhaps more appropriate analogues.

3.3.3.2 Comparison of Yucca Mountain Erosion Rates with Other Semiarid Environments

p. 49 Parts of this discussion are oversimplistic. For example, case-hardened limestones are very resistant to tropical weathering and erosion.

Common desert weathering processes involving salt, insolation, moisture fluctuations, and wind (Goudie, 1989) are not discussed here.

The local relief of Yucca Mountain is an important factor, particularly in relation to canyon incision rates. This discussion of potential weathering and erosion rates is far too cursory. These are major issues which require thorough investigation and discussion.

This discussion of regional denudation rates is oversimplified. Summerfield (1991) pointed out that global, terrestrial denudation rates during the Cenozoic have averaged about 3.0 cm/ka; current rates are about 4.3 cm/ka. However, local rates range from 0.10 cm/ka to 5.0 m/ka depending on climate, local relief, and the nature of the eroding materials.

p. 50 The discussion of "alternative hillslope erosion rates...calculated from hypothetical models that assume that the general hillslope surface may have possessed 2-3 times greater relief than the low-relief model assumed in this study" requires clarification.

3.3.3.3 Evolution of Fortymile Wash

p. 51 The statement that "the net activity recorded by Fortymile Wash during the past 2-3 million years is aggradation" requires explanation. The first scenario in Figure 13 of the TR suggests cyclic cut-and-fill phenomena, with the present channel about 25 m below the highest terrace surface. This suggests net incision over the past 430 ka (suggested age of QTa alluvium in TR is 430 Ka) or so. Earlier episodes of sedimentation and erosion are obscure, so the interpretation that there has been net aggradation is speculative.

3.3.3.4 Stream Incision Rates on Fortymile Wash

pp. 51-52 The depth of incision along Fortymile Wash, especially near the J-13 borehole, would seem to be a critical issue. The rate of incision is indeterminate but based on 100 m relief and local base level, it appears that a potential for over 100 m of incision exists. It is important to ascertain what constraints, if any, there are on reexcavation of the 100 m of alluvium in the wash under different climatic conditions. A key parameter would be future potential base levels especially compared with those just prior to about 430 kabp when the highest terrace was deposited, or just before about 10 kabp if the first scenario presented in Figure 13 of the TR is correct.

Although borehole J-13 and much of Fortymile Wash lie beyond the controlled area, the implications of deep alluvial valley fills in smaller tributary washes and canyons immediately above the proposed repository should be considered. Erosion in the controlled area comparable to excavation of the valley fill near J-13 would lower the land surface to less than 170 m above the repository level. This would constitute a disqualifying condition for the site (10 CFR 960.4-2-6 (d)).

p. 52 In view of the very low erosion rates that are proposed, it would be valuable to ascertain where the sediment filling Fortymile Wash originated. Very rough estimates of the volume of sediment in the watershed indicates higher net denudation rates than the VCR dates suggest. However, it is possible that much of the sediment is older, reworked material, or that some of it is atmospheric fallout originating beyond the watershed. If this is the case, the estimates of net long-term denudation would be markedly different.

3.3.3.5 Downcutting above the Yucca Mountain Surface

p. 54 The possibility that the canyons on the flanks of Yucca Mountain will experience headwall erosion and thereby incise the hillsides laterally rather than vertically should be considered. The origin of such deep (and steep-sided?) erosional features should also be discussed. If they provide evidence of former sapping as a result of groundwater discharge, this would have significant hydrogeological implications for the repository. Moreover, canyon incision rates are calculated based on a 12.7 Ma age for the Tiva Canyon Member of the Paintbrush Tuff which forms the upper bedrock surface. However, incision may have commenced long after deposition or lithification of the tuff. Hence, incision rates could be considerably higher.

3.3.3.6 Summary of Yucca Mountain Erosion Rates

p. 55 The quoted rates of downcutting assume an arbitrary period of incision of about 60 ka. There is no evidence cited to support this.

The statement that it is "unlikely that the wash incised to bedrock during each downcutting episode" requires explanation.

There is no evidence cited to validate the suggestion that "the overall behavior of Fortymile Wash during the Quaternary has been aggradation."

3.4 Technical Evaluation Conclusion

p. 55 Conclusions concerning the geomorphic history of Fortymile Wash and the age of the canyons on Yucca Mountain are highly speculative. No evidence has been presented to help determine the age of the erosional landforms. Only the surrounding surfaces which are thought to be stable have been dated. In themselves, 100 m-deep canyons are very significant geomorphic features, especially in terms of their possible implications concerning the nature of hillslope incision. Their age and mode of formation should be carefully assessed.

Appendix B (Glossary)

p. 59 The terms *denudation* and *erosion* are used interchangeably in the report though here the distinction is made that denudation "is wider in its scope than erosion." Denudation has a broader context both spatially and temporally whereas erosion may refer to very localized phenomena which may also be of short duration.

p. 61 Most of the available climatological data suggest that Yucca Mountain is in the arid zone (i.e., mean annual precipitation is about 150 mm). Yet, the area is repeatedly described as semi-arid.

APPENDIX B

DETAILED COMMENTS AND QUESTIONS ON CATION-RATIO DATING TECHNIQUE USED IN THE DOE TOPICAL REPORT "EVALUATION OF THE POTENTIALLY ADVERSE CONDITION 'EVIDENCE OF EXTREME EROSION DURING THE QUATERNARY PERIOD' AT YUCCA MOUNTAIN, NEVADA"

COMMENT 1

The technical basis for the VCR dating method is not justified in the TR. There are at least three different theories on why cation ratios vary in rock varnish, none of which are discussed in sufficient detail to validate the dating method. Reported variations in cation-ratios may not represent time-dependent processes if two of these theories are supported.

Basis:

The VCR dating technique has received considerable attention since it was first proposed and developed by Dorn (1983). Despite a considerable amount of work on the physical and chemical properties of desert varnish (Perry and Adams, 1978; Potter and Rossman, 1979; Krumbein and Jens, 1981; Dorn and Oberlander, 1982; Dorn, 1984), the exact reasons for apparent variations in the ratio of potassium and calcium to titanium K + Ca/Ti or (KCT) are obscure.

There are three primary models to account for variations in minor element abundances in rock varnish with time. A widely held model is that relatively mobile K and Ca are preferentially leached from accreting varnish while Ti remains immobile, resulting in lower KTC with time (e.g., Dorn, 1983; Dorn and Krinsley, 1991). However, Reneau et al. (1992) concluded that variations in the composition of detrital mineral grains and authigenic mineralization strongly influence the composition of rock varnish, and that these variations in composition invalidate the basic premises of the VCR dating technique. In addition, Reneau and Raymond (1991) and Bierman and Gillespie (1994) have observed that minor element variations in rock varnish were inconsistent with a leaching hypothesis. Instead, they postulated that observed KCT relationships reflect the preferential incorporation of host-rock fragments, which have high KCT ratios, into thin, young varnish deposits. Older, thicker deposits contained relatively fewer host-rock fragments and thus have lower KCT ratios. However, the results of these studies indicate that the amount of substrate incorporation does not vary linearly with time.

If the host rocks for the dated varnish deposits have similar lithologies (i.e., composition, mineralogy, texture), then KCT ratios may vary uniformly with time for these deposits (i.e., Dorn, 1983). However, if different host lithologies are present, then different KCT ratios could be incorporated into the analyzed varnish deposits. This observation is especially significant for the Yucca Mountain region because different host lithologies are used in both calibration standards and dated samples.

Basaltic rocks in the Yucca Mountain region have KCT ratios that are between about 10 to 13 (Table 1-1). These basalts are the primary host for dated varnish deposits at Skull Mountain, Little Skull Mountain, Buckboard Mesa, and Crater Flat. However, talus deposits at Yucca Mountain consist of fragments of welded rhyolitic ignimbrite, which are primarily from the Tiva Canyon member of the Paintbrush Tuff (DOE, 1988). KCT ratios for Tiva Canyon rhyolite are about 60, but decrease to about 30 for less abundant quartz latite members (Broxton et al., 1989). These ignimbrites also are the dominant lithologies in the alluvial deposits used to construct part of the cation-ratio calibration curve for Yucca Mountain (Harrington and Whitney, 1987; and Whitney and Harrington, 1993). Thus, two distinct lithologies (basaltic lava and welded rhyolitic ignimbrite) are used to construct the cation-ratio calibration curve for Yucca Mountain.

If the hypothesis of Reneau and Raymond (1991) and Bierman and Gillespie (1994) is accepted, then a linear relationship may not exist between the 40–255 ka ignimbrite hosts and the 1.1 Ma basaltic hosts on the Yucca Mountain cation-ratio calibration curve. The KCT ratios of these two lithologies should represent two different cation-ratio trends that originate at different initial KCT ratios that reflect the different host lithologies. In addition, measured KCT ratio variations on samples of unknown age may reflect variations in the amount of substrate fragments incorporated into the varnish and not accurately represent the age of the deposit.

Recommendation:

Further discussion on the basis for cation ratio dating is required before reported cation-ratio variations can be accepted as accurate age estimates for Quaternary deposits. The hypotheses that cation-ratio variations may represent different degrees of substrate contamination, amount or composition of the underlying substrate, composition of deuteric minerals, or authigenic mineralization, need to be tested and disproven to validate this dating technique.

References:

Bierman, P.R., and A.R. Gillespie. 1994. Evidence suggesting that methods of rock-varnish cation-ratio dating are neither comparable nor consistently reliable. *Quaternary Research* 41: 82-90.

Broxton, D.E., R.G. Warren, F.M. Byers Jr., and R.B. Scott. 1989. Chemical and mineralogic trends within the Timber Mountain-Oasis Valley caldera complex, Nevada: Evidence for multiple cycles of chemical evolution in a long-lived silicic magma system. *Journal of Geophysical Research* 94(B5): 5961-5985.

Dorn, R.I. 1983. Cation-ratio dating: A new rock varnish age-determination technique. *Quaternary Research* 20: 49-73.

Dorn, R.I. 1984. Cause and implications of rock varnish microchemical laminations. *Nature* 310: 767-770.

Dorn, R.I., and T.M. Oberlander. 1982. Rock varnish. *Progress in Physical Geography* 6: 317-367.

Dorn, R.I., and D.H. Krinsley. 1991. Cation-leaching sites in rock varnish. *Geology* 19:1077-1080.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Krumbein, W.E., and Jens, K. 1981. Biogenic rock varnishes of the Negev Desert (Israel): an ecological study of iron and manganese transformation by cyanobacteria and fungi. *Oecologia* 50: 25-38.

Perry, R.S., and J.B. Adams. 1978. Desert varnish: evidence for cyclic deposition of manganese. *Nature* 276: 489-491.

Potter, R.M., and G.R. Rossman. 1979. The manganese- and iron-oxide mineralogy of desert varnish. *Chemical Geology* 25: 79-94.

Reneau, S.L., and R. Raymond, Jr. 1991. Cation-ratio dating of rock varnish: Why does it work? *Geology* 19: 937-940.

Reneau, S.L., R. Raymond, Jr., and C.D. Harrington. 1992. Elemental relationships in rock varnish stratigraphic layers, Cima volcanic field, California: Implications for varnish development and the interpretation of varnish chemistry. *America Journal of Science* 292:684-723.

U.S. Department of Energy. 1988. *Site Characterization Plan (Site Geology).* DOE/RW-0160. Washington, D.C.: U.S. Department of Energy: I, Chapter 1.2.

Whitney, J.W., and C.D. Harrington. 1993. Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada. *Geological Society of America Bulletin* 105:1008-1018.

COMMENT 2

Different types of rock varnish may be present in an area, of which only some are suitable for cation-ratio dating (Dorn, 1989; Krinsley et al.,1990; Dorn and Krinsley, 1991). The TR does not address how different types of rock varnish were recognized, nor if different types of varnish textures were present in the studied rocks. Measured cation-ratio variations may represent the analysis of different textural types of rock varnish that will not represent the age of the deposit.

Basis:

Rock varnish on a single surface may be texturally inhomogeneous and include sites where varnish chemistry may have been influenced by cracking, proximity to the soil, organic matter accumulation, biogenic activity, or ponding of water (Dorn, 1989; Krinsley et al., 1990). These disturbed sites are not suitable for cation-ratio dating studies because they may represent cation ratio variations that developed independent of time (e.g., Dorn and Krinsley, 1991).

Dorn and Krinsley (1991) measured KCT ratios at the Little Cone volcano, which is part of the Quaternary volcanic alignment that includes Black Cone and Red Cone (e.g., Vaniman et al., 1982). KCT ratios for Little Cone layered-texture varnish are 2.7 ± 0.2 (1 sigma), which is comparable to reported values of 2.2 ± 0.3 and 2.3 ± 0.1 for Black Cone and Red Cone, respectively (Harrington and Whitney, 1987). However, porous-texture varnish at Little Cone has a KCT ratio of 1.9 ± 0.4. Although the Dorn and Krinsley (1991) values are each within the range of 1 sigma error reported for Black and Red Cones, the Little Cone data suggests that Black and Red Cone KCT ratios could be mixtures of layered-texture and porous-texture varnish. Similar textural variations likely affect KCT ratios in other deposits. Thus, textural variations in varnish may produce some of the KCT variations attributed solely to age. The relationship between varnish texture and KCT ratio is not discussed in the TR.

Recommendation:

The hypothesis that variations in varnish cation-ratios may be affected by differences in varnish texture needs to be tested and disproven before reported cation-ratios can be related to time-dependent processes.

References:

Dorn, R.I. 1989. Cation-ratio dating of rock varnish: A geographical perspective. *Progress in Physical Geography* 13:559-596.

Dorn, R.I., and D.H. Krinsley. 1991. Cation-leaching sites in rock varnish. *Geology* 19:1077-1080.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Krinsley, D.H., R.I. Dorn, and S. Anderson. 1990. Factors that may interfere with the dating of rock varnish. *Physical Geography* 11:97-119.

Vaniman, D.T., B.M. Crowe, and E.S. Gladney. 1982. Petrology and geochemistry of Hawaiite lavas from Crater Flat, Nevada. *Contributions to Mineralogy and Petrology* 80: 341-357.

COMMENT 3

Varnish from two compositionally and texturally distinct rock substrates may not be directly comparable. Variations in VCRs may be influenced by differences in substrate composition or texture, and not represent time-dependent processes.

Basis:

The two primary lithologies in the Yucca Mountain Region analyzed for cation-ratios are Neogene basalt and rhyolitic ignimbrite. Geochemical analyses in Table B-1 show that KCT ratios for basalt are at least 10, but increase to at least 60 for rhyolitic ignimbrite. Rock varnish is a complex assemblage of authigenic and detrital minerals (e.g., Potter and Rossman, 1977). Local variations in bedrock mineralogy can provide different detrital mineral assemblages in rock varnish (Reneau et al., 1992). In addition, authigenic mineral compositions and abundances in varnish may be controlled by the composition of the host rock (Harrington and Whitney, 1987; Raymond et al., 1988; Reneau et al., 1992). If the hypothesis that variations in varnish cation-ratios is due to preferential leaching of K and Ca with time is accepted (e.g., Dorn, 1983), then the composition of the underlying substrate may directly affect the composition of the rock varnish (Reneau et al., 1992).

Varnish deposition also is controlled by the microtopography of the substrate (Dorn and Oberlander, 1982; Dorn and Krinsley, 1991; Reneau et al., 1992). Local microtopographic lows more readily trap detrital mineral grains and collect water for authigenic mineral formation, resulting in relatively thick varnish layers (e.g., Reneau et al., 1992). Basaltic lavas and rhyolitic ignimbrites have obvious difference in macroscopic and microscopic textural features, including the presences of vesicles, groundmass porosity and permeability, amounts of groundmass glass and crystals, abundances and sizes of primary minerals, and the morphologies and abundances of fissures and joints (e.g., Vaniman et al., 1982; Bish and Chipera, 1989). Each of these textural features could influence the development of rock varnish, and textural differences between the lava and ignimbrite thus could result in variations in rock varnish thickness and composition.

Table B-1. KCT ratios for basaltic rocks in the Yucca Mountain region, Nevada.

	Weight Percent			ppm	Mole Percent					
Crowe et al, 1986	TiO_2	CaO	K_2O	Ba	Ti	Ca	K	Ba	K+Ca/Ti	$\frac{K+Ca}{Ti+0.33\ Ba}$
Black Cone	1.50	8.90	1.60	1220	0.017	0.16	0.03	0.003	11	11
Red Cone	1.30	9.00	1.60	1400	0.015	0.16	0.03	0.003	13	13
Buckboard Mesa	1.50	7.00	2.30	2100	0.017	0.12	0.05	0.003	10	10
Little Skull Basalt	1.55	10.67	0.92	1024	0.018	0.19	0.02	0.003	12	12
Little Skull B And	1.28	8.20	1.74	821	0.015	0.15	0.04	0.003	12	12
Broxton et al., 1989										
Tiva Rhyolite	0.14	0.26	4.74	51	0.002	0.005	0.10	0.003	65	64
Tiva QTZ Latite	0.48	1.69	5.70	2098	0.006	0.03	0.12	0.003	27	25

Recommendation:

The influence of textural differences between lava and ignimbrite host lithologies on varnish development must be determined before variations in varnish cation-ratios can be robustly linked to a time-dependent process.

References:

Bish, D.L., and S.J. Chipera. 1989. *Revised Mineralogic Summary of Yucca Mountain, Nevada.* LA-11497-MS. Los Alamos National Laboratory.

Crowe, B.M., K.H. Wohletz, D.T. Vaniman, E. Gladney, and N. Bower. 1986. *Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations.* LA-9325-MS, Vol. II. Los Alamos, NM: Los Alamos National Laboratory.

Dorn, R.I. 1983. Cation-ratio dating: A new rock varnish age-determination technique. *Quaternary Research* 20: 49-73.

Dorn, R.I., and D.H. Krinsley. 1991. Cation-leaching sites in rock varnish. *Geology* 19:1077-1080.

Dorn, R.I., and T.M. Oberlander. 1982. Rock varnish. *Progress in Physical Geography* 6:317-367.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Potter, R.M., and G.R. Rossman. 1977. Desert varnish: The importance of clay minerals. *Science* 196:1446-1448.

Raymond, R., Jr., C.D. Harrington, D.L. Bish, and S.J. Chipera. 1988. Mineralogic characterization of rock varnish from Nye County, southern Nevada. *Geological Society of America Abstracts* 20-7:A345.

Reneau, S.L., R. Raymond, Jr., and C.D. Harrington. 1992. Elemental relationships in rock varnish stratigraphic layers, Cima volcanic field, California: Implications for varnish development and the interpretation of varnish chemistry. *America Journal of Science* 292:684-723.

Vaniman, D.T., B.M. Crowe, and E.S. Gladney. 1982. Petrology and geochemistry of Hawaiite lavas from Crater Flat, Nevada. *Contributions to Mineralogy and Petrology* 80: 341-357.

COMMENT 4

The Uranium-trend (U-trend) dating method is used to determine the age of coarse-grained alluvial deposits used in the calibration curve. Available data indicates that the precision and accuracy of these uranium-trend dates are significantly lower than reported in the TR.

Basis:

In the TR, three of the five calibration points are dated using U-trend methods. Swadley et al. (1984) used these same dates to estimate the ages of Quaternary soils and alluvial deposits in the vicinity of Yucca Mountain. They noted that the dating method was experimental and "that accuracy of the absolute ages derived by this method is not known... (Swadley et al., 1984: p. 6). Geyh and Schleicher (1990: p. 226) also question whether U-trend dates actually represent the age of the deposit. No data have been presented in the TR to demonstrate that the U-trend dates used in the calibration curve either precisely or accurately represent the age of the varnish associated with these deposits. Although Harrington et al. (1988: p. 1052) stated that the "analytical uncertainty in the K-Ar and U-series SIC dates is minimal", the Los Alamos peer-review group felt that "additional calibration points should use all suitable methods" (Birkeland et al., 1989: p. 6). The VCR calibration curve used for this study apparently has not been modified or tested in any way since it was originally published by Harrington and Whitney (1987).

It is not possible to directly correlate the samples dated by the uranium-trend method (Rosholt et al., 1985) with calibration units Q2c, Q2b, and CF, using the limited data presented in the TR or associated publications. Although unpublished U-trend dates by D.R. Muhs are used in Table 1 of Harrington and Whitney (1987), these dates are not presented in the TR and cannot be evaluated for precision or accuracy. Numerous sites for units Q2c, Q2b, and CF are however, presented in Rosholt et al. (1985), but there is no discussion of the range in apparent ages of these units in Harrington and Whitney (1987). The 40$\pm$10 ka "Crater Flat surface" reported in Harrington and Whitney (1987) apparently corresponds to unit Q2a in Rosholt et al. (1985), which has an apparent range in age from 30$\pm$10 to 55$\pm$20 ka in the Yucca Mountain area. Unit Q2b, which has a reported age of 160$\pm$20 ka in Harrington and Whitney, ranges in age from 160$\pm$25 to 200$\pm$80 ka in Rosholt et al. (1985). Unit Q2c, which has a reported age of 255$\pm$15 ka in Harrington and Whitney, ranges in age from 240$\pm$50 to 310$\pm$40 ka for the upper member reported in Rosholt et al. (1985). Clearly, the precision and accuracy of the dates associated with units Q2c, Q2b, and CF is significantly lower than reported in Harrington and Whitney (1987).

Rosholt et al. (1985) report that gravels in the upper member of unit Q2c "locally overlie and contain reworked cinders from the Big Dune basalt center 11 km northwest of Lathrop Wells," Nevada. Although earlier K-Ar dates for this volcano (Vaniman et al., 1982) are between 200 and 300 ka, these dates are generally regarded as erroneously old (e.g., Crowe et al., 1992). Relatively high-precision Ar-Ar (Turrin et al., 1991) and cosmic-ray exposure dates (e.g., Crowe et al., 1992; Zreda et al., 1993) indicate that the age of the "Big Dune" volcano is likely 100$\pm$50 ka. Thus, unit Q2c should be significantly younger that the 255$\pm$15 ka age used in the VCR calibration curve for the TR. Likewise, the ages of overlying units Q2b and CF may also be significantly younger than represented by the U-series dates.

Recommendation:

The relationship between uranium-trend dates of alluvial deposits and associated varnish ages needs to be established. Apparent ambiguities between U-trend dates used in the TR and those in Rosholt et al. (1985) must be addressed. If these dates do not accurately or precisely represent varnish ages, then these data cannot be correctly used in a calibration curve. If the uranium-trend technique is presumed to be a valid dating technique for the calibration points, then it is logical to conclude that this method also could be used to test the accuracy and precision of reported cation ratio dates through the analysis of fine-grained eolian sediments trapped within colluvial boulder deposits.

References:

Birkeland, P.W., T.M. Oberlander, and J.W. Hawley. 1989. *Peer review report on rock-varnish studies within the Yucca Mountain Project.* Los Alamos National Laboratory, Earth and Space Sciences Division, Geology and Geochemistry Group (ESS-1): 8 pp.

Crowe, B., R. Morley, S. Wells, J. Geissman, E. McDonald, L. McFadden, F. Perry, M. Murrell, J. Poths, and S. Forman. 1992. The Lathrop Wells volcanic center: Status of field and geochronology studies. *Proceedings of the Third International High Level Radioactive Waste Management Conference.* La Grange Park, IL: American Nuclear Society: 1,997-2,013.

Geyh, M.A., and H. Schleicher. 1990. *Absolute Age Determination.* New York, NY: Springer Verlag.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Harrington, C.D., Dethier, D.P., and Whitney, J.W. 1988. Reply to comment on "Scanning electron microscope method for rock-varnish dating." *Geology* 16: 1051-1052.

Rosholt, J.N., C.A. Bush, W.J. Carr, D.L. Hoover, W.C. Swadley, and J.R. Dooley, Jr. 1985. *Uranium-Trend Dating of Quaternary Deposits in the Nevada Test Site Area, Nevada and California.* U.S. Geological Survey Open-File Report 85-540. Reston, VA: U.S. Geological Survey.

Swadley, W.C., D.L. Hoover, and J.N. Rosholt. 1984. *Preliminary Report on Late Cenozoic Faulting and Stratigraphy in the Vicinity of Yucca Mountain, Nye County, Nevada.* U.S. Geological Survey Open-File Report 84-788. Reston, VA: U.S. Geological Survey.

Turrin, B.D., D. Champion, and R.J. Fleck. 1991. $^{40}Ar/^{39}Ar$ age of the Lathrop Wells Volcanic Center, Yucca Mountain, Nevada. *Science* 253: 654-657.

Vaniman, D.T., B.M. Crowe, and E.S. Gladney. 1982. Petrology and geochemistry of Hawaiite lavas from Crater Flat, Nevada. *Contributions to Mineralogy and Petrology* 80: 341-357.

Zreda, M.G., F.M. Phillips, P.W. Kubik, P. Sharma, and D. Elmore. 1993. Cosmogenic ^{36}Cl dating of a young basaltic eruption complex, Lathrop Wells, Nevada. *Geology* 21: 57-60.

COMMENT 5

Uncertainties for VCRs used to calculate dates in this report do not represent the uncertainties commonly associated with SEM-EDS analyses and likely underestimate analytical error.

Basis:

Two measures of uncertainty are provided in Table 4 of the TR: the standard deviation of the mean VCR for a deposit (S_{CR}) and a 95-percent CL for the mean cation-ratio, calculated from Bierman et al. (1991). The 95-percent CL value is then used to calculate the uncertainty in the cation-ratio dates, because it is believed to more accurately measure the true uncertainty in the VCRs than S_{CR} (TR; Bierman et al., 1991; Whitney and Harrington, 1993). Although neither calculation accurately reflects the error associated with SEM-EDS analyses, the 95-percent CL uncertainties will underestimate the error associated with VCR analyses more than the S_{CR} uncertainties.

Bierman et al. (1991) pointed out that "because varnish samples collected from different boulders are not identical, S_{CR} (sample standard deviation of the cation-ratio) for multiple boulders on a single geomorphic surface should exceed σ_{CR} (the precision of each cation-ratio determination)." It is not possible to rigorously evaluate the uncertainties and dates presented in Table 4 of the TR without knowing the analytical uncertainty associated with the VCR analyses. However, this uncertainty can be estimated from other studies that report analytical information more completely.

Bierman et al. (1991) noted that for SEM-EDS analyses of rock varnish, analytical uncertainty in the VCR is about 10 percent for count times of 200 s. This uncertainty was determined on the same type of EDS system used in the TR analyses, with a 15-keV accelerating voltage and a 10 nA beam current on the SEM. In the TR, accelerating voltages apparently ranged from 15 keV for Crater Flat analyses to 30 keV for Black and Red Cone analyses, resulting in detector dead-times of 15–20 percent for count times of 150 s (Harrington and Whitney, 1987). Although Bierman et al. (1991) do not report detector dead-times, their analytical conditions appear very similar to those used in this report and analytical errors thus should be analogous.

Harrington and Whitney (1987) report that replicate analyses of 22 samples gave VCRs that varied about 4 percent between two analytical runs. This error does not represent the uncertainty associated with the VCR analyses, but rather reflects the reproducibility of the analyses. Average VCR analyses have reported analytical errors that range between 5 and 24 percent and average 14 percent (Table B-2) (Harrington and Whitney, 1987). In addition, cation-ratios by Reneau et al. (1992) were determined by analytical methods that are very similar to those apparently used in the TR, and have approximate analytical precisions of 5 percent for K, 7 percent for Ca, and 13 percent for Ti. This analytical error is consistent with a 10-percent error generally associated with SEM-EDS analyses for K, Ca, and Ti (Bierman et al., 1991; Reneau et al., 1992).

Thus, VCR analytical errors (i.e., σ_{CR}) are estimated at 10 percent for the data in the TR. However, average uncertainties in the VCRs are 9 percent for the S_{CR} of the Yucca Mountain region data, but decrease to 3 percent using the 95-percent CL (Table B-2). It is not intuitive how uncertainties of 3 percent (i.e., the 95-percent CL) can accurately represent analyses with individual errors of at least 10 percent. Although neither measure of uncertainty incorporates the analytical uncertainty associated with these data (cf. Comment 6), the S_{CR} values likely are more representative of the uncertainty associated with the VCRs used for dates. Using the S_{CR} for date calculations, average error on the VCR dates increases from 6 percent (i.e., 95-percent CL) to 22 percent (Table B-2).

Recommendation:

A discussion of the analytical errors associated with individual VCRs needs to be included in the TR. Individual analyses should be reported in order to evaluate population statistics and assumptions. Analytical error needs to be included as a measure of uncertainty in the VCR dates.

Table B-2. Cation-Ratio dates from Whitney and Harrington.

Unit	Sample	Reported # Sites	KCT	1 Scr	95%CL		Calculated %Error in KCT (KCT/Err) w/ 1 Scr	w/ 95%CL
Yucca Mtn	YME-1	55	2.99	0.19	0.05		6	2
Yucca Mtn	YME-2	80	4.52	0.55	0.12		12	3
Yucca Mtn	YMW-1	55	3.34	0.47	0.13		14	4
Yucca Mtn	YMW-2	40	2.97	0.08	0.03		3	1
Yucca Mtn	YMW-3	65	2.88	0.19	0.05		7	2
Yucca Mtn	YMN-1	40	2.79	0.27	0.09		10	3
L. Skull Mtn	LSM-1	160	2.52	0.21	0.03		8	1
Skull Mtn	SKM-1	45	2.74	0.21	0.06		8	2
Skull Mtn	SKM-2	30	2.68	0.16	0.06		6	2
Skull Mtn	SKM-3	35	2.28	0.26	0.09		11	4
Skull Mtn	SKM-3A	50	2.49	0.11	0.03		4	1
Buckboard Mesa	BM-1	40	2.09	0.35	0.11		17	5
						Average	**9**	**3**

Calculations using calibration from Harrington & Whitney (1987): (KCT=10.466-2.667 log t) and above data

Unit	Sample	Reported Date (ka)	Range	Calculated date w/ 95%CL ka	-1s	+1s	Avg %Err		Calculated date w/ Scr ka	-1s	+1s	Avg %Err
Yucca Mtn	YME-1	640	610-670	640	610	660	4		640	540	750	16
Yucca Mtn	YME-2	170	140-180	170	150	190	12		170	110	270	47
Yucca Mtn	YMW-1	465	400-515	470	420	520	11		470	310	700	41
Yucca Mtn	YMW-2	645	630-660	650	630	660	2		650	600	690	7
Yucca Mtn	YMW-3	710	680-740	700	670	730	4		700	590	820	16
Yucca Mtn	YMN-1	760	710-820	760	700	810	7		760	600	950	23
L. Skull Mtn	LSM-1	960	930-990	950	930	980	3		950	800	1140	18
Skull Mtn	SKM-1	800	760-830	790	750	830	5		790	660	950	18
Skull Mtn	SKM-2	830	800-880	830	790	870	5		830	720	950	14
Skull Mtn	SKM-3	1180	1110-1270	1170	1090	1270	8		1170	940	1470	23
Skull Mtn	SKM-3A	990	960-1030	980	950	1010	3		980	890	1080	10
Buckboard Mesa	BM-1	1380	1260-1510	1380	1250	1520	10		1380	1020	1870	31
						Average	**6**					**22**

Representative analyses:		Harrington & Whitney (1987) KCT	Std Error	%Err		Whitney & Harrington (1993) (Estimated uncertainties from error bars) KCT	± Err	%Err
Yucca Mtn	BC	2.18	0.27	12		2.18	0.10	5
Yucca Mtn	RC	2.33	0.11	5		2.33	0.10	4
Yucca Mtn	Q2c	4.34	1.04	24		4.34	0.20	5
Yucca Mtn	Q2b	4.68	0.52	11		4.68	0.15	3
Yucca Mtn	CF	6.00	1.00	17		6.00	0.25	4
			Average	**14**				**4**

References:

Bierman, P.R., A.R. Gillespie, and S. Kuehner. 1991. Precision of rock-varnish chemical analyses and cation-ratio ages. *Geology* 19: 135-138.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Reneau, S.L., R. Raymond, Jr., and C.D. Harrington. 1992. Elemental relationships in rock varnish stratigraphic layers, Cima volcanic field, California: Implications for varnish development and the interpretation of varnish chemistry. *America Journal of Science* 292: 684-723.

Whitney, J.W., and C.D. Harrington. 1993. Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada. *Geological Society of America Bulletin* 105: 1,008-1,018.

COMMENT 6

Reported uncertainties fail to incorporate analytical error ($\approx$10 percent) and thus do not accurately reflect uncertainties in VCR dates.

Basis:

The uncertainties reported in the TR (S_{CR} and 95-percent CL) fail to propagate analytical error through calculations, resulting in average uncertainties that are less than analytical errors. The standard deviation of the absolute VCR values may significantly underestimate the actual uncertainty in the data set and result in VCR dates that have erroneously low uncertainties.

An accurate determination of the mean and standard deviation of a data set that has significant analytical errors can be calculated by propagating n sample analytical errors ($X_i \pm x_i$) through the basic statistical calculations

$$\bar{X} \pm \bar{x} = \frac{\sum X_i}{n} \pm \frac{\sqrt{\left(\sum x_i^2\right)}}{n} \qquad \text{(B-1)}$$

where $\bar{x}$ = Uncertainty in the average (i.e., σ_{CR})

$\bar{X}$ = Average of n samples (i.e., CR)

Assuming the data are normally distributed:

$$\text{Sdev} = \sqrt{\frac{\sum \left(X_i \pm x_i - \bar{X} \pm \bar{x}\right)^2}{n-1}} \qquad \text{(B-2)}$$

The uncertainty associated with the mean VCR will thus increase when analytical error is propagated, but this value will more accurately represent the error associated with the VCR analyses than a standard deviation calculated without propagation of analytical error. The reported S_{CR} values (Table B-2) thus underestimate the standard deviation of the VCR analyses because analytical error has not been propagated through the calculations.

On this basis, the uncertainties in the VCR ratios from this TR cannot be accepted as an accurate representation of the uncertainty in the analyses used to determine these ratios. The reported uncertainties underestimate the uncertainties most likely associated with these data. The 95-percent CL values (Table B-2) also underestimate KCT uncertainty, because these values incorporate S_{CR} in their calculation (Bierman et al., 1991).

Recommendation:

The individual analyses and associated uncertainties must be provided for each of the 12 sample sites before the true uncertainty associated with the cation-ratio dates can be determined.

References:

Bierman, P.R., A.R. Gillespie, and S. Kuehner. 1991. Precision of rock-varnish chemical analyses and cation-ratio ages. *Geology* 19: 135-138.

COMMENT 7

The calibration curve used to calculate cation-ratio dates does not represent the uncertainty associated with the data used to construct the curve.

Basis:

Each of the five data points used in the calibration curve have an uncertainty associated with the measured KCT ratio and the age of the deposit. This uncertainty must be incorporated into all date calculations (e.g., Harden et al., 1988), and cannot be simply ignored because a correlation coefficient of 0.992 is determined on the linear regression.

The uncertainty in the calibration curve cannot be accurately determined from the data presented in the TR. As noted in Question 2, the error bars in Figure 9 of the TR are 75 percent smaller than in the source of the original data (Harrington and Whitney, 1987) (Figure B-1A vs B-1B). However, one estimate of the uncertainty in a linear correlation can be determined by calculating a 95-percent confidence interval, which is based on the standard deviation of the data set. The 95-percent confidence intervals for the Yucca Mountain calibration curves were calculated using the SigmaPlot (Version 5.0, 1992) statistics program. For a KCT ratio of 2.99 ± 0.19 (TR, sample YME-1), this apparent uncertainty in the calibration curve results in a date uncertainty that increases from ± 30 ka in the TR to +380 -260 ka (Figure B-2B).

Recommendation:

Uncertainties in the VCR analyses and dates for points on the calibration curve must be incorporated into reported VCR dates.

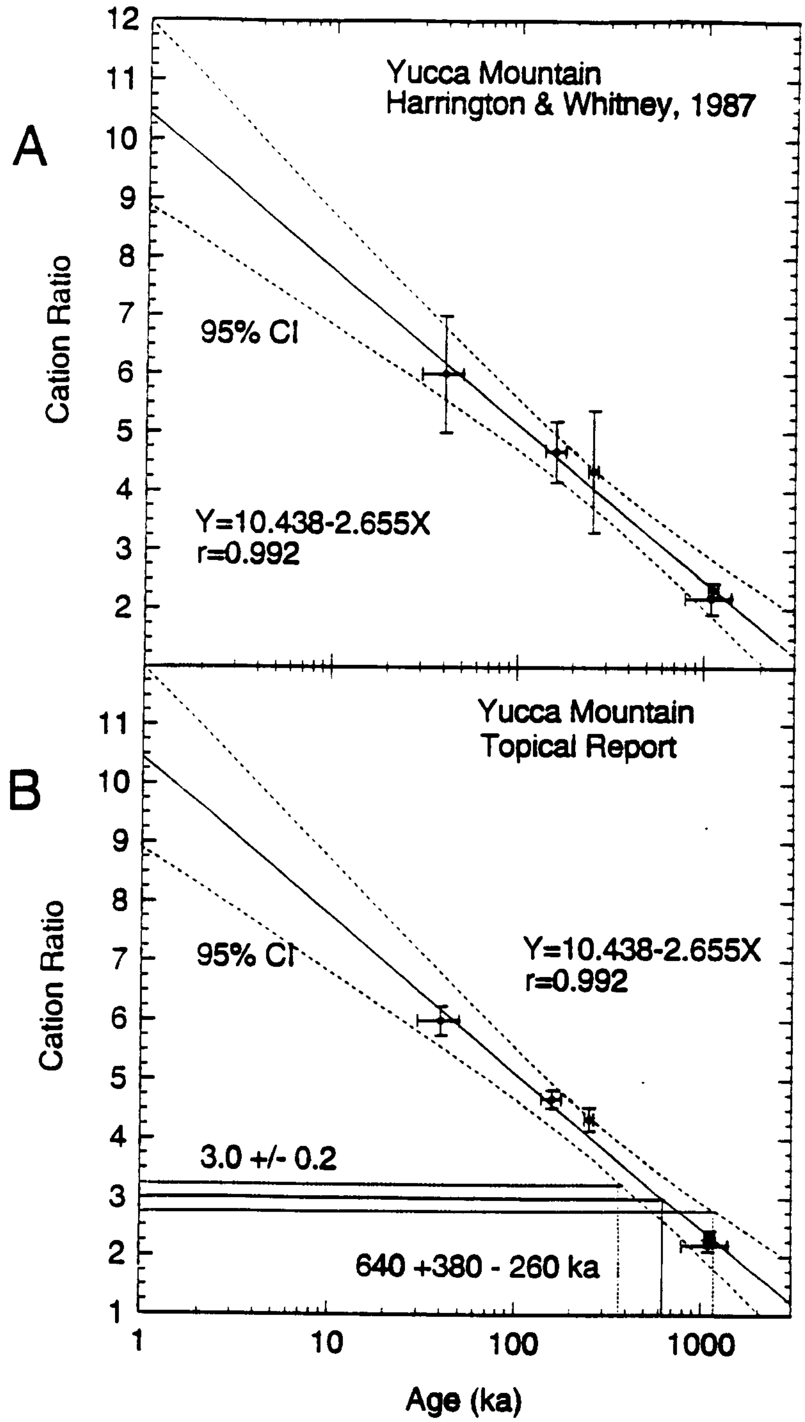


Figure B-1. (A) VCR dates and uncertainties from Harrington and Whitney, 1987. Cation Ratios for these samples are 75 percent smaller in the TR (Figure 4-1B). (B) Uncertainty in the scope of the calibration curve (estimated by a 95 percent confidence interval) affects date uncertainty significantly.

References:

Harden, J.W., M.C. Rheis, J.M. Sowers, and J.L. Slate. 1988. Comment on "Scanning electron microscope method for rock-varnish dating" by Harrington and Whitney, 1987. *Geology* 16: 1051.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

COMMENT 8

The criteria used to discard individual VCR analyses from all sample sets is neither transparent nor robust. Reported average VCRs are systematically biased towards older dates (i.e., lower VCRs).

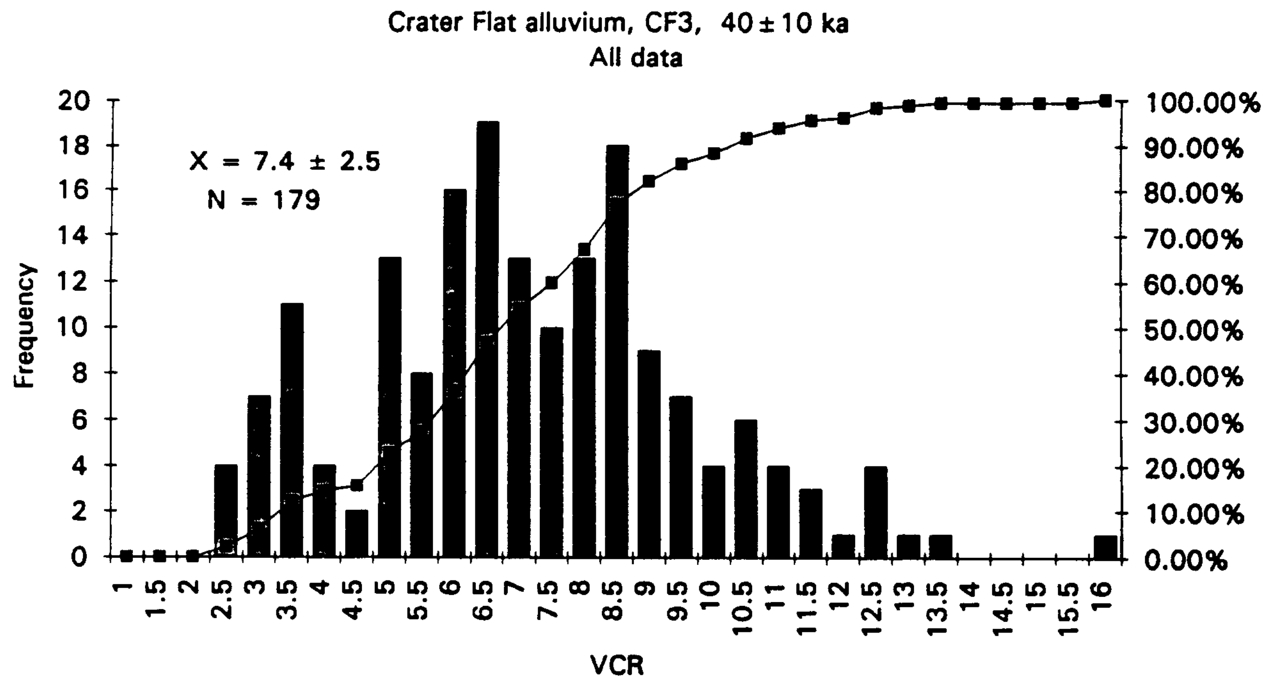
Basis:

Apparently 20 boulders were sampled for each of 12 deposits, and a subset of 8 to 10 samples were selected for analysis based on "the quality of each varnish coat (p. 40)." Two circular sample disks with areas greater than 3 cm^2 were prepared for each boulder when possible, and 6 overlapping 25 mm^2 sites on each disk were analyzed. Thus, each deposit should have at least 48 analytical sites (8 samples, 1 disk each, 6 analyses per disk) as a minimum, and ideally around 100 analytical sites (8 to 10 samples, 2 disks each, 6 analyses per disk). However, half of the deposits have less than 48 reported analytical sites, and only 1 deposit (LSM-1) has more than 80 analytical sites.

The TR states that "... If the varnish chemistry from one clast is anomalous compared to that from the other clasts and the majority of varnish clasts possess a consistent varnish chemistry... then the analyses from the anomalous clast are disregarded during calculation of the cation-ratio for that deposit." Based on the number of analytical sites reported in Table 4, at least 1 sample (i.e., 6–12 analyses) was discarded from every deposit. There is no justification presented as to what constitutes an "anomalous" sample, except to note that high VCR values are anomalous.

Average VCR values for all samples in this study are calculated after discarding around 50 percent of the individual analyses. Although the rationale for discarding 50 percent of the data is not presented in the TR, Harrington and Whitney (1987) state that they "excluded the highest VCR site on each disk and the highest rock VCR for each deposit." Apparently, "high" VCR values are regarded as anomalous.

Using the VCR data available for three calibration points (Q2c, Q2b, and CF), there is no obvious distinction between VCR values that are regarded as anomalously "high" and not included in average calculations and the population used in further calculation. If all analyses are considered, the VCR values for the CF sample have a roughly normal distribution (Figure B-2), although a possible low-value population may be represented between 2.5 and 4.5. Discarding 50 percent of the data (Harrington and Whitney, 1987) further enhances the low-value population, and decreases the average VCR from 7.4 ± 2.5 to 6.1 ± 1.6 (i.e., 7 ± 3 to 6 ± 2). Unit Q2b (Figure B-3) has a highly skewed to log-normal population distribution, which again provides no obvious distinction between "anomalously high" VCRs and the remaining population. The VCR data for Q2c (Figure B-4) also lack a distinction between "anomalously high" values and "high" values that are part of the normal population distribution. Discarding the "anomalously high" values lowers the average VCR from 7 ± 3 to 6 ± 2 for unit Q2b, and from 5 ± 2 to 5 ± 1 for unit Q2c.



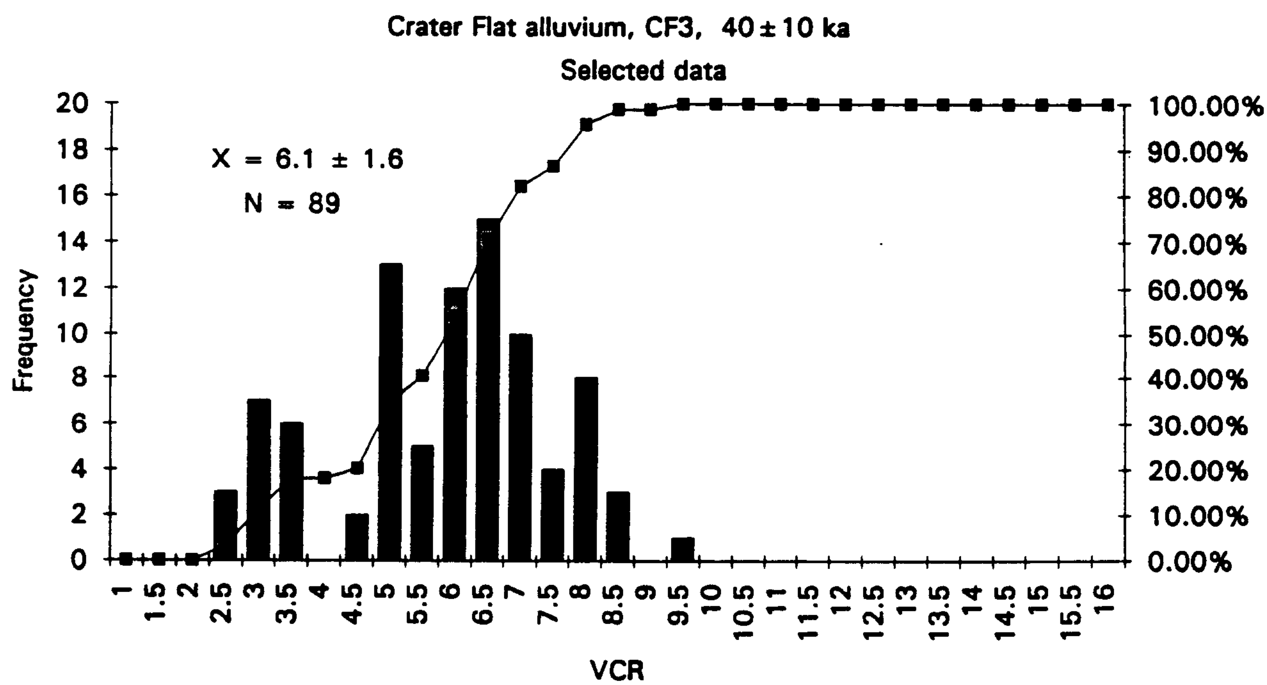
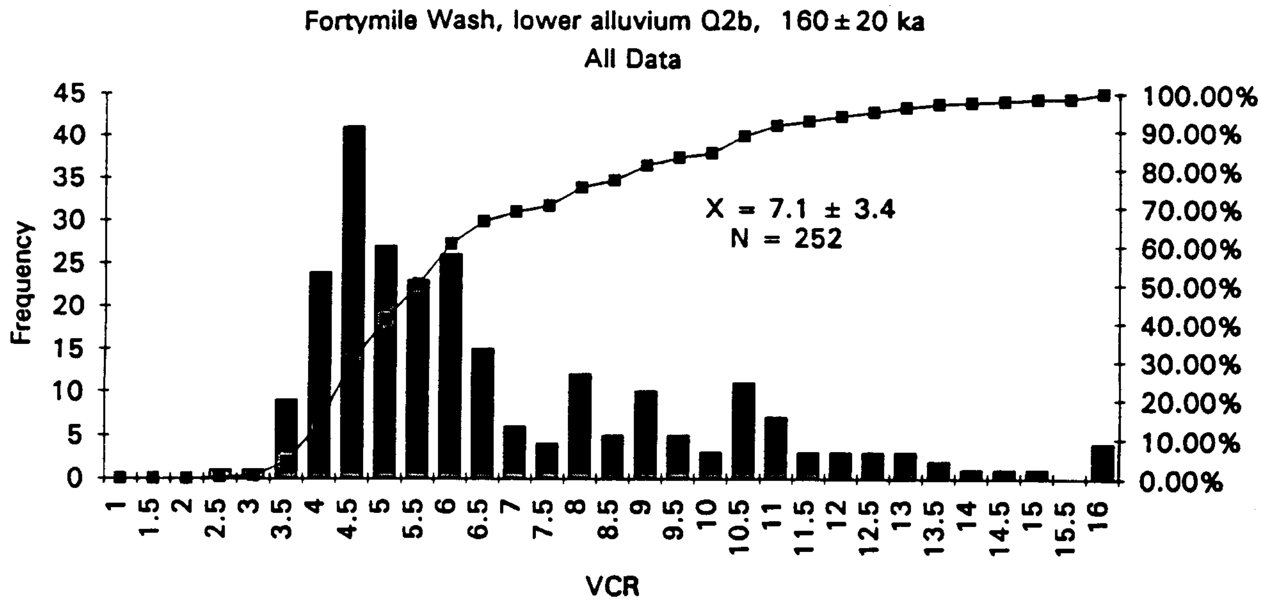


Figure B-2. VCR data for Crater Flat alluvium.



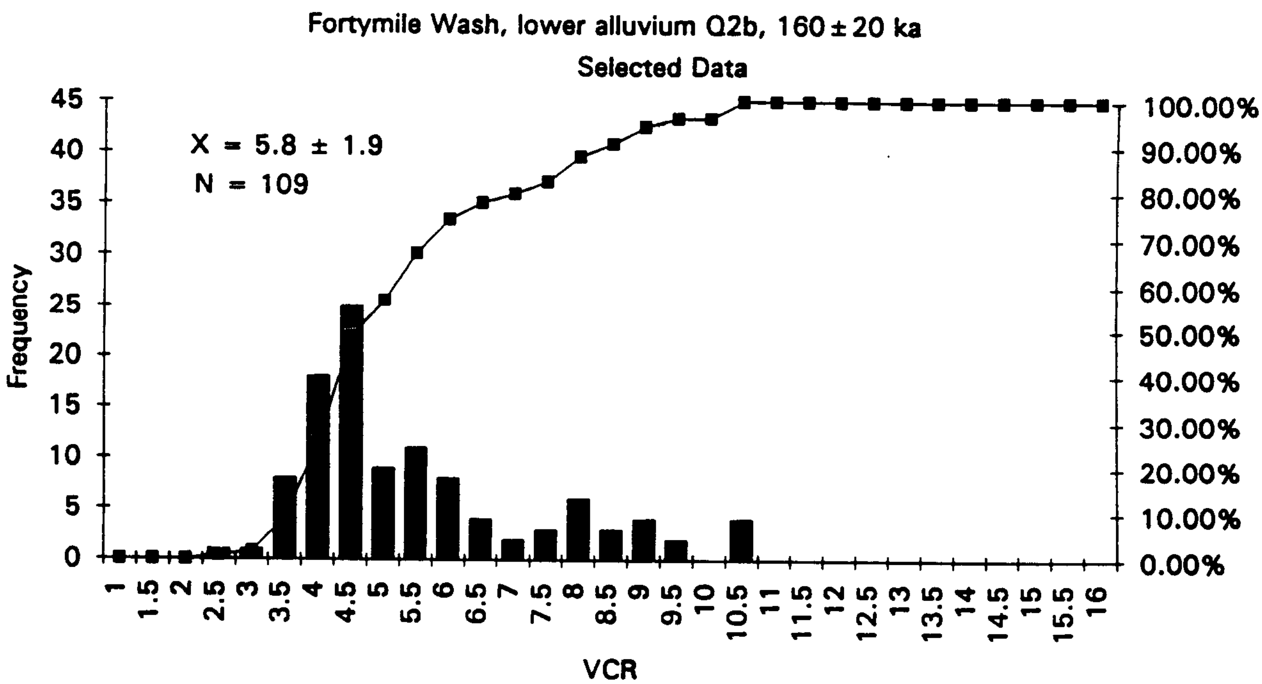
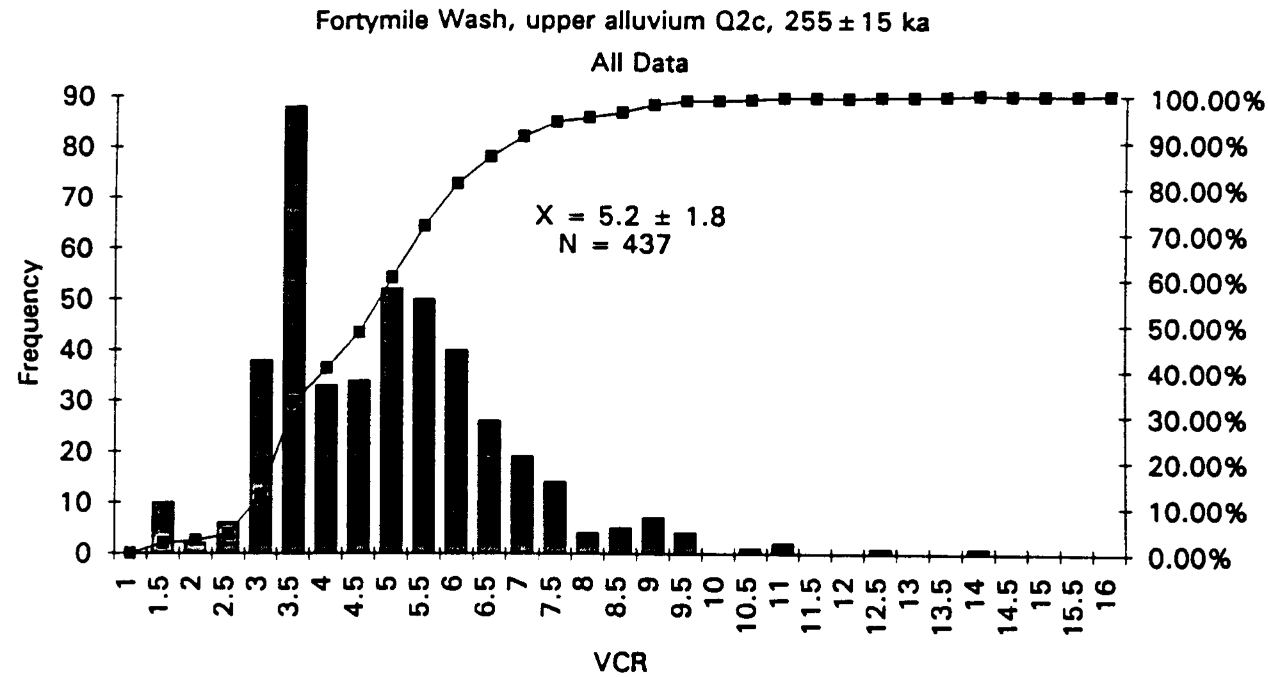


Figure B-3. VCR data for Fortymile Wash Q2B alluvium.



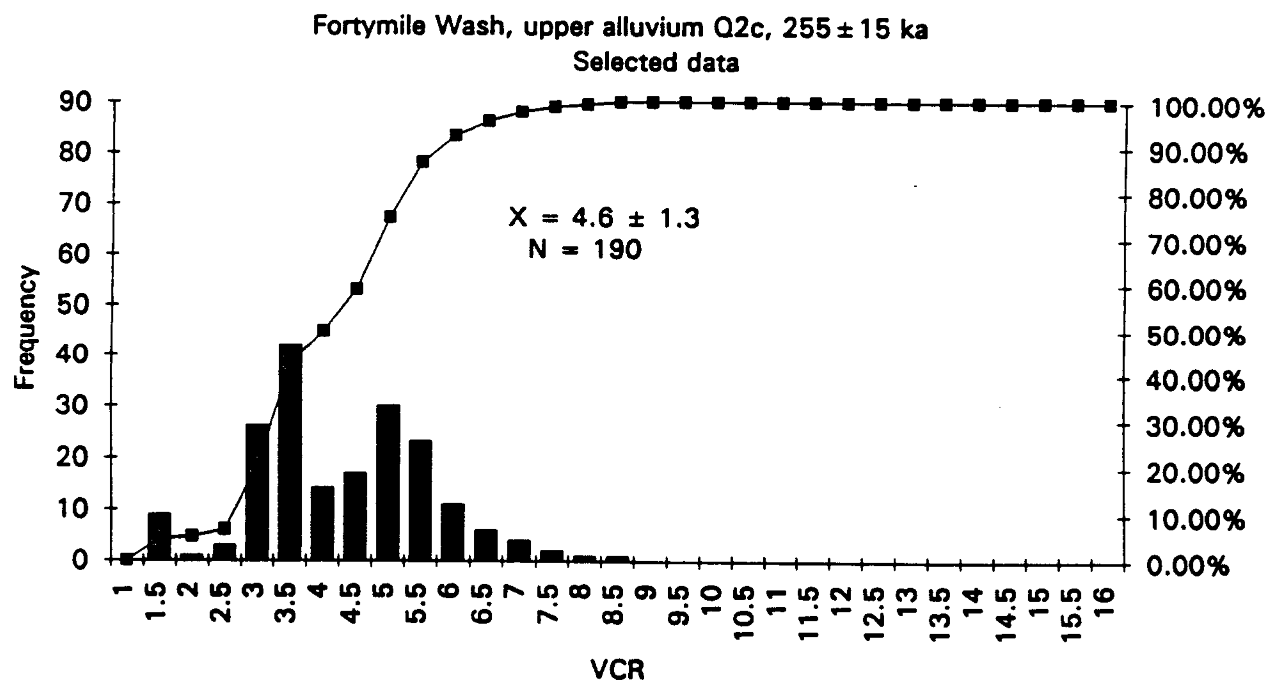


Figure B-4. VCR data for Fortymile Wash Q2C alluvium.

As noted in Comment 2, textural variations in rock varnish also may result in VCR values that are anomalously low (Dorn and Krinsley, 1991). In addition to substrate contamination, high VCR values may result from changes in initial varnish chemistry and authigenic mineralization (e.g., Reneau et al., 1992; Bierman and Gillespie, 1994). All of these processes represent a continuum between average or representative varnish VCRs and anomalous VCR values. Systematically discarding high VCR values from calculations of VCR averages will incorrectly bias these averages to lower values and artificially reduce the variation in the VCR population. This procedure will result in dates that are incorrectly old and have associated uncertainties that are incorrectly low. Additional bias towards older samples also may be introduced by the lack of calibration on samples <40 kabp.

Recommendation:

The basis for discarding analyses from each sample must be justified. The apparent procedure in the TR will incorrectly bias the reported VCRs towards older apparent dates with incorrectly low uncertainties.

References:

Bierman, P.R., and A.R. Gillespie. 1994. Evidence suggesting that methods of rock-varnish cation-ratio dating are neither comparable nor consistently reliable. *Quaternary Research* 41: 82-90.

Dorn, R.I., and D.H. Krinsley. 1991. Cation-leaching sites in rock varnish. *Geology* 19: 1,077-1,080.

Harrington, C.D., and Whitney, J.W. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Reneau, S.L., R. Raymond, Jr., and C.D. Harrington. 1992. Elemental relationships in rock varnish stratigraphic layers, Cima volcanic field, California: Implications for varnish development and the interpretation of varnish chemistry. *America Journal of Science* 292: 684-723.

COMMENT 9

The Topical Report (TR) does not adequately address the potentially adverse condition of evidence for extreme erosion during the Quaternary period. Instead, the TR focuses on long-term denudation as evidenced by dating relict boulder fields.

Basis:

As was pointed out in the CNWRA comments on the outline for this TR (Center for Nuclear Waste Regulatory Analyses, 1992), a distinction must be made between regional denudation and more localized erosional phenomena. The major portion of the TR deals with dating of hillslope deposits which are presumed to be geomorphically stable. Estimates of rates of incision of channels adjacent to the stable boulder deposits are provided but there is little discussion of rates of incision along the canyons and washes, or of scarp retreat and other backwearing phenomena which are fundamentally distinct from regional lowering of the land surface. While the terms *denudation* and *erosion* are often used interchangeably (for example, Kearey, 1993), for the purposes of this study, they should be clearly defined and differentiated.

It is essential to ascertain whether the time periods which are used to calculate the erosion rates during the Quaternary are appropriate for this evaluation of possible evidence of extreme erosion. NUREG-0804 (Nuclear Regulatory Commission, 1983: p. 382) defines extreme erosion as the "occurrence of substantial changes in landforms (as a result of erosion) **over relatively short intervals of time**" (emphasis added). Hence, estimates of erosion rates based on net erosion over hundreds of thousands or even millions of years may be inappropriate. It is feasible that much of the incision of a surface which is 500,000 yr old could have occurred over perhaps 10,000 yr or less. If this is the case, the shorter time interval could constitute a period of extreme erosion. However, averaged over a 500,000 yr interval, estimated erosion rates would be 50 times less than the actual rates during the erosional episode. It is inappropriate to assume that the mean conditions which have prevailed over the past million years or so (perhaps 12 million yr in the case of estimated canyon incision rates) will be replicated over the next 10,000 yr. The intent of 10 CFR 60.122 (c) (16) must be carefully considered.

The foregoing observation calls into question the whole concept underlying the approach to this study. By dating stable geomorphic surfaces, the study is more likely to provide an impression of landscape stability than if its focus was the dating of erosional landforms and events. It would be valuable to estimate the likely range in erosion rates by comparing, for example, 1,000 or 10,000 yr of an interpluvial episode (such as the Holocene) with a period of similar length during a pluvial cycle (such as that from about 25 to 15 kabp).

Nowhere in this TR is the issue of projecting Quaternary rates of erosion to evaluate potential significant effects on isolation of the waste addressed. While this is not strictly within the scope of the document, the intent of 10 CFR 60.122 (a)(2) cannot be ignored. Extrapolation of Quaternary erosion rates into the future must incorporate an evaluation of likely future modifications of antecedent environmental conditions. The first of the two key issues is to assess whether the area has experienced any paleoenvironmental conditions during the Quaternary which resulted in extreme rates of erosion that could threaten waste isolation. Second, it must be determined whether such extreme phenomena or other conditions can be reasonably anticipated at the site in the next 10,000 yr. If erosion rates during the Quaternary can be demonstrated to be benign relative to a potential effect on waste isolation, then the potentially adverse condition 10 CFR 60.122(c)(16) can be said to be absent.

Recommendation:

The premise that evidence of extreme erosion during the Quaternary period can be determined by dating geomorphic surfaces that have presumedly remained stable for long periods of time must be validated. Because erosion rates in the TR were determined over relatively long intervals of time, there is a distinct possibility that the occurrence of accelerated or even catastrophic erosional events is overlooked. It should be proven that during the course of the Quaternary it is unlikely that there have been marked variations in erosion rates in the geologic setting which, if they occurred at Yucca Mountain, might significantly affect the waste isolation capability of the site.

References:

Center for Nuclear Waste Regulatory Analyses. 1992. *Comments on DOE Erosion Topical Report Outline*. San Antonio, TX. Center for Nuclear Waste Regulatory Analyses: 13 p.

Kearey, P. 1993. *The Encyclopedia of the Solid Earth Sciences*. Oxford, England: Blackwell Scientific: 713 pp.

U.S. Nuclear Regulatory Commission. 1983. Staff Analysis of Public Comments on Proposed Rule 10 CFR Part 60, Disposal of High-Level Radioactive Wastes in Geologic Repositories. Office of Nuclear Regulatory Research. NUREG-0804. Washington, DC: Nuclear Regulatory Commission: 563 pp.

U.S. Nuclear Regulatory Commission. 1991. *Disposal of High-Level Radioactive Wastes in Geologic Repositories*. Title 10, Energy, Part 60 (10 CFR Part 60). Washington, DC: U.S. Government Printing Office.

COMMENT 10

The interpretation that the late Pleistocene from about 25 to 10 thousands of years before present (kabp) was a period of comparative geomorphic inactivity on the hillslopes of the Yucca Mountain area is contrary to some of the evidence from neighboring areas such as the Mojave Desert.

Basis:

The TR not only suggests that very little hillslope erosion occurred during the late Pleistocene but also that there was not a great deal of weathering on the upper hillslopes. This is contrary to some of the evidence from neighboring areas such as the Mojave Desert, where Oberlander (1989: p. 71) noted that a late Pleistocene colluvial mantle is currently eroding. This reflects a significant change in geomorphic processes from the late Pleistocene to Holocene time in the Mojave Desert.

It is widely believed that over most of the earth, the Last Glacial Maximum (LGM) at about 18 ka BP experienced the lowest mean annual temperatures of any time during the Quaternary. It therefore seems unlikely that frost weathering could have occurred on the upper slopes of Yucca Mountain during the early and middle Pleistocene (as is proposed in the TR) but not at the LGM. This apparent anomaly requires further explanation and corroboration. In the TR, discussion of the variations in mean winter temperatures and the influence of winter precipitation on rates of frost weathering needs clarification and elaboration. In the absence of supporting evidence, it would seem probable that the boulder beds are not as ancient as purported in this study, or perhaps they were formed by processes other than frost weathering. Elsewhere in the southwest United States, the late Pleistocene is represented by significant colluviation on lower hillslopes (Dorn, 1984; Reneau et al., 1986; Dorn et al., 1987) and major changes in the character of pedogenesis (Gile, 1966, 1975, 1977; Gile and Grossman, 1968; Birkeland, 1992).

Overall, the paleoenvironmental history that has been proposed in the TR requires additional consideration. Most of the glacial features in northern Nye County are attributed to a late (terminal) Pleistocene age (Kleinhampl and Ziony, 1985). It seems likely that late Pleistocene climate was at least as cold and probably colder than at any other time during the Quaternary Period. The proposed antiquity of the boulder deposits implies that they were formed during relatively warmer periods of the Quaternary. The reasoning behind the suggested lack of such boulder deposits forming during the cooler portion of the Quaternary (i.e., the late Pleistocene) should be discussed.

Recommendation:

Additional data must be presented to corroborate the atypical paleoenvironmental interpretations for the southwestern United States presented in this TR. Proposed origin of the boulder deposits must be reconciled with the paleoenvironmental history of the Yucca Mountain region.

References:

Birkeland, P.W. 1992. Quaternary soil chronosequences in various environments - extremely arid to humid tropical. *Weathering, Soils, and Paleosols*. I.P. Martini and W. Chesworth, eds. Elsevier, Amsterdam: 261-281.

Dorn, R.I. 1984. Cause and implications of rock varnish microchemical laminations. *Nature* 310: 767-770.

Dorn, R.I., M.J. DeNiro, and H.O. Ajie. 1987. Isotopic evidence for climatic influence on alluvial-fan development in Death Valley. *Geology* 15: 108-110.

Gile, L.H. 1966. Cambic and certain non-cambic horizons in desert soils of southern New Mexico. *Proceedings of the Soil Science Society of America* 30: 773-781.

Gile, L.H. 1975. Holocene soils and soil-geomorphic relations in an arid region of southern New Mexico. *Quaternary Research* 5: 321-360.

Gile, L.H. 1977. Holocene soils and soil-geomorphic relations in a semiarid region of southern New Mexico. *Quaternary Research* 7: 112-132.

Gile, L.H., and R.B. Grossman. 1968. Morphology of the argillic horizon in desert soils of southern New Mexico. *Soil Science* 106: 6-15.

Kleinhampl, F.J., and J.I. Ziony. 1985. *Geology of Northern Nye County, Nevada*. Nevada Bureau of Mines & Geology Bulletin 99-A: Reno, NV: University of Nevada.

Oberlander, T.M. 1989. Slope and pediment systems. In: *Arid Zone Geomorphology*. D.S.G. Thomas, ed. London, Belhaven: 56-84.

Reneau, S.L., W.E. Dietrich, R.I. Dorn, C.R. Berger, and M. Rubin. 1986. Geomorphic and paleoclimatic implications of latest Pleistocene radiocarbon dates from colluvium-mantled hollows, California. *Geology* 14: 655-658.

COMMENT 11

The proposed origin of the dated boulder deposits in the TR is equivocal. These boulder deposits may not be related to frost weathering, and alternative interpretations may significantly affect paleoclimatic scenarios presented in the TR.

Basis:

Frost-weathering is proposed in the TR as the predominant mechanism for forming hillslope boulder deposits. Although there is strong evidence that parts of the American southwest experienced glacial and periglacial conditions at times during the Quaternary, the paleoclimatic information for the existence of such conditions at Yucca Mountain is less than convincing (e.g., Comment 9). It is important to note Oberlander (1989: p. 66) concluded that "whereas alpine talus has attracted much study, desert talus has received minimal attention." The precise erosional mechanisms resulting in boulder deposits are diverse, so the resulting landforms may not necessarily be characteristic of a specific climatic regime.

In the TR it is argued that hillside boulder stripes are probably of periglacial origin. Certainly, the features appear to resemble cryogenic landforms (Prokopovich, 1987) but other possible origins cannot be summarily dismissed. For example coarse talus slopes occur in many desert environments which have not been subjected to frost weathering during the Quaternary. Mechanical weathering as a result of temperature fluctuations (insolation), periodic wetting and desiccation, and salt impregnation have all been invoked to account for granular disintegration of rock in arid settings (Goudie, 1989). In this context, it is significant that Harrington and Whitney (1987: p. 970) concluded that "higher accumulation rates and more alkaline composition of dust probably resulted from deflation of dry playas that persisted over great aerial (*sic*) extent and for long periods of time" near Yucca Mountain during the Pleistocene. Such dust deposits are often saline and salts are commonly an important, even pre-eminent, factor in desert weathering processes (Goudie, 1989; Watson, 1992; Cooke et al., 1993).

The boulder beds also may be lag accumulations, which are subjected to gradual lowering without appreciable lateral displacement. There are numerous examples of coarse residual lags which accumulate as finer matrix material is removed by both surface and subsurface erosion (Stocking, 1978; Bull et al., 1987). Oberlander (1989) described varnished boulders being lowered on hillslopes as fines are eroded. This example was from Arizona in an area receiving about 180-mm mean annual rainfall, which is just 30 mm (20 percent) more than that estimated for Yucca Mountain.

Recommendation:

The paragenesis of the boulder deposits must be reconciled with the paleoclimatic processes thought to operate in the Yucca Mountain region. The origin of the hillslope boulder deposits should be unequivocally related to cryogenic or periglacial processes in order to support the proposed paleoclimatic models for the Yucca Mountain region.

References:

Bull, P.A., A.S. Goudie, D. Price Williams, and A. Watson. 1987. Colluvium: a scanning electron microscope study of a neglected sediment type. *Clastic Particles*, J.R. Marshall, ed. New York, NY: Van Nostrand Reinhold: 16-35.

Cooke, R., A. Warren, and A. Goudie. 1993. *Desert Geomorphology*. London, England: UCL: 526.

Goudie, A.S. 1989. Weathering processes. *Arid zone geomorphology*. D.S.G. Thomas, ed. London, Belhaven: 11-24.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Oberlander, T.M. 1989. Slope and pediment systems. In: *Arid Zone Geomorphology*. D.S.G. Thomas, ed. London, England: Belhaven: 56-84.

Prokopovich, N.P. 1987. Rock stripes on Sierra Nevada foothills. *California Geology* 40: 27-30.

Stocking, M.A. 1978. Interpretation of stone-lines. *South African Geographical Journal* 60: 121-134.

Watson, A. 1992. Desert soils. *Weathering, Soils and Paleosols*. I.P. Martini and W. Chesworth, eds. Amsterdam, Elsevier: 225-260.

COMMENT 12

The complete removal of pre-existing varnish is a critical assumption in the proposed dating technique. Although the TR presumes that rock varnish is resistant to erosion and thus accumulates at a time-dependent rate, other information in the TR suggests that varnish may not be completely removed during down-slope transport or may not be resistant to weathering processes.

Basis:

The TR assumes that down-slope transport of boulders will remove the "soft and easily eroded rock varnish (p. 35)." Although some data are presented in the TR to support the hypothesis that down-slope transport occurs by debris-flow processes with concomitant varnish erosion, other transport processes also are possible. For example, down-slope transport of coarse boulder deposits by "dry block creep" has been described for some desert environments (Cooke et al., 1993). Varnish may be preserved on boulders moving by creep or other gentle mass-wasting processes

In the TR it is argued that the varnish coatings are too fragile to be preserved on moving boulders. Dorn and Oberlander (1982) reported varnish with a hardness approaching 6.5 Moh. Allen (1978) contended that varnish in the Sonoran Desert is destroyed only by sandblasting. The implications of these observations should be assessed in the context of the varnished boulder deposits on and around Yucca Mountain.

Elsewhere in the TR, it is stated that the varnish protects the boulders from weathering processes. A physically fragile rock-varnish may be chemically resistant to weathering, however, this relationship must be demonstrated.

Merrill (1898) and Engel and Sharp (1958) held that varnish is generally brittle and readily decomposes under moist conditions. Whitney and Harrington (1993) described hillslope boulders on Yucca Mountain that have been split at some time following the formation of desert varnish on their surfaces. If this splitting also is attributed to frost weathering, it may not be possible to reconcile frost-weathered splitting with the fact that the varnish must therefore have been preserved and unaffected during a cool and moist climatic episode.

Recommendation:

The assumption that pre-existing rock varnish is completely removed before deposit stabilization needs to be critically assessed. The presumed resistance of rock varnish to physical and chemical weathering processes also needs to be evaluated in detail.

References:

Allen, C.C. 1978. Desert varnish of the Sonoran Desert - optical and electron probe analysis. *Journal of Geology* 86: 743–752.

Cooke, R., A. Warren, and A. Goudie. 1993. *Desert Geomorphology*. London, England: UCL: 526.

Dorn, R.I., and T.M. Oberlander. 1982. Rock varnish. *Progress in Physical Geography* 6: 317–367.

Engel, C.G., and R. Sharp. 1958. Chemical data on desert varnish. *Bulletin of the Geological Society of America* 69: 487–518.

Merrill, G.P. 1898. Desert varnish. *Bulletin of the United States Geological Survey* 150: 389–391.

Whitney, J.W., and C.D. Harrington. 1993. Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada. *Bulletin of the Geological Society of America* 105: 1,008–1,018.

COMMENT 13

The section of the TR which deals with reported denudation rates from other areas with similar climates and also other areas of North America fails to consider the complex relationships between local geologic controls and climate.

Basis:

The intent of providing denudation rates in TR Tables 2 and 3 and the accompanying discussion is evidently to show that the erosion rates determined for Yucca Mountain using the VCR dating technique are very low in comparison to most arid and semi-arid regions. However, since there is an abundance of data concerning this issue, it should be stressed that the information provided in the TR is merely a representative sample. Certain data have been omitted even from the cited sources [for example, additional data from less arid parts of Australia quoted by Bishop (1985)].

It would be valuable to provide some additional information on, for example, how variations in relief affect erosion rates, or how rates of weathering may influence rates of erosion on different lithologies under various climatic regimes. Some of this material has been discussed by Summerfield (1991), who provided a succinct overview of global-and continental-scale denudation rates and the ways in which local factors can influence differential rates of erosion. In this context, it is important to address the issue of potential rates of regional denudation and more localized erosional incision of the landscape. Variations in local relief, changes in base levels resulting from tectonic activity, the impact of climatic change on weathering rates, and the physical and chemical properties of both the lithified and unlithified surface materials are all significant influences on rates of erosion.

It is important to realize that regional denudation can result from many diverse processes. In temperate regions of the northern hemisphere, glaciation has commonly had a brief but very dramatic impact on long-term erosion rates. In the tropics, notably in Africa and Australia, some land surfaces appear to have been essentially stable for over 100 million yr or more. Even here, however, chemical denudation as a result of subsurface weathering has lowered apparently relict landscapes by several tens of meters (Tardy, 1992; Tardy and Roquin, 1992). Similar chemical denudation occurs in many areas of limestone bedrock, though its surface expression is both more varied and complex than volcanic terrains.

In the case of Yucca Mountain, it is important to consider whether hillslope lowering is a representative process in regional denudation. Backwearing of the hillslopes and mountain sides by peripheral scarp retreat along canyons or fault-bounded free-faces may be more significant than hillslope lowering. Investigations of the geomorphic stability of upper hillslopes would tend to overlook such processes or minimize their importance in terms of the regional denudation chronology. Similarly, low areas currently mantled by thick colluvial, alluvial, and eolian deposits may be potentially more susceptible to incision as a result of erosion by streams and rivers under suitable conditions. An investigation of current and potential regional base levels in Fortymile Wash and the Amargosa River basin should clarify some of these issues of the potential erodibility of the land surface.

Recommendation:

Erosion-rate comparisons between the Yucca Mountain region and other regions in the world need to consider the effects of local differences in geologic and topographic conditions. Regional base levels and the aggradational or degradational character of locally important drainages need to be discussed.

References:

Bishop, P. 1985. Southeast Australian late Mesozoic and Cenozoic denudation rates: a test for late Tertiary increases in continental denudation. *Geology* 13: 479–482.

Summerfield, M.A. 1991. *Global Geomorphology*. Harlow, England: Longman Scientific and Technical.

Tardy, Y. 1992. Diversity and terminology of lateritic profiles. *Weathering, Soils and Paleosols*, I.P. Martini and W. Chesworth, eds. Amsterdam, The Netherlands: Elsevier: 379–405.

Tardy, Y., and C. Roquin. 1992. Geochemistry and evolution of lateritic landscapes. Weathering, Soils and Paleosols., I.P. Martini and W. Chesworth, eds. Amsterdam, The Netherland: Elsevier: 407–443.

QUESTION 1

What is the basis for selecting dates of 1.12±0.07 Ma for Red Cone and 1.1±0.3 Ma for Black Cone varnishes used in the calibration curve, when multiple dates of varying precision and accuracy are available for these volcanoes?

Basis:

The K-Ar dates for Black and Red Cones, which are used to construct the calibration curve, may not be as precise and accurate as reported. Red Cone has numerous K-Ar dates besides the 1.12±0.07 Ma listed in Harrington and Whitney (1987), which range from 0.95±0.11 to 1.9±0.2 Ma (Sinnock and Easterling, 1983; Vaniman et al., 1982). Black Cone also was dated at 1.1±0.4 Ma (Vaniman et al., 1982), in addition to the 1.1±0.3 Ma date in Harrington and Whitney (1987). No criteria are presented in the original reference (Harrington and Whitney, 1987) or subsequent reports (Whitney and Harrington, 1993; TR) on why 1.12±0.07 Ma and 1.1±0.3 Ma are selected as the respective ages of Red and Black Cones.

Recommendation:

Additional justification is needed as to why the reported dates for Red and Black Cones accurately represent the ages of these volcanoes, but other published dates are inaccurate.

References:

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Sinnock, S., and R.G. Easterling. 1983. *Empirically Determined Uncertainty in Potassium-Argon Ages for Plio-Pleistocene Basalts from Crater Flat, Nye County, Nevada*. SAND 82-2441. Albuquerque, NM: Sandia National Laboratory.

Vaniman, D.T., B.M. Crowe, and E.S. Gladney. 1982. Petrology and geochemistry of Hawaiite lavas from Crater Flat, Nevada. *Contributions to Mineralogy and Petrology* 80: 341-357.

Whitney, J.W., and C.D. Harrington. 1993. Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada. *Geological Society of America Bulletin* 105: 1,008-1,018.

QUESTION 2

Why are the error bars for the VCRs in the calibration curve roughly 75 percent smaller than reported in the original reference (Harrington and Whitney, 1987), when apparently identical analytical methods were used?

Basis:

Figure B-1 compares the VCR errors in the calibration curve of Harrington and Whitney (1987) with those of the TR and Whitney and Harrington (1993). Analytical methods used in the TR appear nearly identical to those used by Harrington and Whitney (1987), which is repeatedly cited as the source of the calibration data.

The TR does not state that the standards were reanalyzed. However, counting times were increased from 100 s (Harrington and Whitney, 1987) to 150 s (TR). As noted by Bierman et al. (1991), analytical uncertainties decrease as a function of the square root of the counting (i.e., dwell) time. It appears that counting time for standards was increased between Harrington and Whitney (1987) and the TR.

Recommendation:

If the standards were reanalyzed using different techniques than those of Harrington and Whitney (1987), then a more complete description of analytical methods is needed.

References:

Bierman, P.R., A.R. Gillespie, and S. Kuehner. 1991. Precision of rock-varnish chemical analyses and cation-ratio ages. *Geology* 19: 135-138.

Harrington, C.D., and J.W. Whitney. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

Whitney, J.W., and C.D. Harrington. 1993. Relict colluvial boulder deposits as paleoclimatic indicators in the Yucca Mountain region, southern Nevada. *Geological Society of America Bulletin* 105:1008-1018.

QUESTION 3

What is the basis for using the standardless semiquantitative (SSQ) program for VCR analyses when this program may not accurately determine Ti abundances in the presence of Ba?

Basis:

In the TR, the VCRs are calculated using the SSQ program described by Harrington and Whitney (1987). However, Harrington et al. (1991) stated that "the inadequacy of SSQ to provide reliable Ti concentrations in the presence of Ba suggests the need for a reanalysis, using MICRO Q or SQ, of the rock-varnish samples used in the calibration of the rock varnish dating curve of Harrington and Whitney (1987)." Yet in this TR (p. 42) it is stated that "the rock-varnish dating curve for Yucca Mountain (Harrington and Whitney, 1987) was calibrated using cation-ratios calculated from data derived using the SSQ program. Thus, the age estimates for these colluvial boulder deposits are obtained by plotting SSQ-generated cation-ratios on this dating curve..." It is unclear whether the correction for Ba content in order to determine the VCR (using [Ca + K]/[Ti + 1/3] Ba instead of [Ca + K]/Ti) has been used to recalculate the VCRs of the calibration samples or whether it is merely adopted to bring the boulder deposit VCR data into conformity with the earlier calibration sample analyses. This confusion requires careful clarification. If the present VCR data do not correspond to those used to determine the calibration curve, the accuracy of the dating is seriously compromised.

Recommendation:

The continued use of the SSQ program despite the comments of Harrington et al. (1991) must be justified.

References:

Harrington, C.D., D.J. Krier, R. Raymond, and S.L. Reneau. 1991. Barium concentration in rock varnish: implications for calibrated rock varnish dating curves. *Scanning Microscopy* 5: 55-62.

Harrington, C.D., and Whitney, J.W. 1987. Scanning electron microscope method for rock-varnish dating. *Geology* 15: 967-970.

QUESTION 4

What amount of VCR variation occurs on analyses of the same disk, for varnish samples from the same boulder, and for boulders from the same deposit?

Basis:

The degree of varnish heterogeneity must be determined before average VCR values can be used to calculate dates for boulder deposits. As demonstrated in numerous studies (e.g., Dorn and Krinsley, 1991; Bierman et al., 1991; Reneau et al., 1992), significant heterogeneity may exist in the VCRs for each sample disk, for the varnish on a boulder, and between boulders in the same deposit. These potential variations cannot be evaluated with the limited data presented in the TR.

VCRs for each deposit in the TR are calculated by discarding an unspecified number of analyses, averaging all VCRs obtained for each boulder in a deposit, then averaging all the boulder averages for the deposit. This procedure obscures the true VCR variation that may occur within a deposit, and likely results in incorrectly low estimates of uncertainty.

Recommendation:

Individual analyses, including those discarded from the data set, need to be provided in order to independently assess sample and deposit heterogeneity, to calculate VCR statistics, and to test the statistical significance of variations in sample populations.

References:

Bierman, P.R., A.R. Gillespie, and S. Kuehner. 1991. Precision of rock-varnish chemical analyses and cation-ratio ages. *Geology* 19: 135-138.

Dorn, R.I., and D.H. Krinsley. 1991. Cation-leaching sites in rock varnish. *Geology* 19:1077-1080.

Reneau, S.L., R. Raymond, Jr., and C.D. Harrington. 1992. Elemental relationships in rock varnish stratigraphic layers, Cima volcanic field, California: Implications for varnish development and the interpretation of varnish chemistry. *America Journal of Science* 292: 684-723.

APPENDIX C

PRELIMINARY NRC/CNWRA CONCERNS WITH EXTREME EROSION TOPICAL REPORT

1. SCOPE OF THE TOPICAL REPORT

CONCERN 1

The Topical Report (TR) does not adequately address extreme erosion during the Quaternary period but rather addresses primarily long-term denudation as evidenced by dating relict boulder fields. Most of the hillslope surfaces in the YMR lack relict boulder fields, which may indicate that erosion has removed these deposits and that calculated erosion rates are significantly in error.

CONCERN 2

The methods used to calculate long-term average hillslope degradation rates, quoted in TR Table 5 (p. 48), could underestimate the rates of erosion which have occurred in the Yucca Mountain region during individual (short-term) periods of erosion because pre-erosional topography cannot be determined. As a result, the staff is unable to determine how the DOE will calculate reasonable rates of erosion which can be expected during the proposed repository's period of performance.

CONCERN 3

The rate of canyon cutting quoted on page 55 of the TR apparently does not include erosion of stratigraphic units considered to overlie the Tiva Canyon member of the Paintbrush Tuff. As a result, the TR could underestimate the past erosion rates in the Yucca Mountain region within such canyons. Since the canyon cutting rate cited on TR page 55 is expressed in terms of incision into an unknown thickness of Miocene volcanics nearly 13 million years old, the staff is uncertain what methodology the DOE will use for determination of the rate of canyon cutting expected to occur during the period of performance.

2. RELIANCE UPON A SINGLE CONTROVERSIAL DATING METHOD

CONCERN 4

The basis for the VCR dating method is not justified in the TR. Research by Dorn and Krinsley (1991), Reneau and Raymond (1991), and Reneau et al. (1992) indicates that the basis for VCR dating, the preferential leaching of K and Ca relative to immobile Ti, is not supported by available data. The basis for relating variations in VCR to a time-dependent process must be addressed before the reported VCR variations can be related to deposit dates.

CONCERN 5

Different types of rock varnish may be present in an area, of which only some are suitable for cation-ratio dating (Dorn, 1989; Krinsley et al., 1990; Dorn and Krinsley, 1991). The TR does not, but should, address how different types of rock varnish were recognized and if different types of varnish textures were present in the studied rocks. Some researchers believe that measured cation-ratio variations may result from analysis of different textural types of rock varnish rather than differences in the ages of the deposits.

CONCERN 6

Varnish from two compositionally and texturally distinct rock substrates, such as the basalt lava and rhyolite tuff used in the calibration curve, may not be directly comparable. Variations in VCRs may be influenced by differences in substrate composition or texture in addition to time-dependent processes.

CONCERN 7

U-trend dates are used for three of the five points in the VCR calibration curve. If this technique is suitable for dating calibration points, then it is not clear why this technique could not be applied to the hillslope boulder deposits as a test of the VCR dates. In addition, it is not clear what samples in the original source of the dates (Rosholt et al., 1985) were analyzed for VCRs, because the dates reported by Harrington and Whitney (1987) for units Q2c (255±15 ka) and Q2b (160±20) are not present in Rosholt et al. (1985), and data from Muhs (1986, unpublished data) have not been reported.

CONCERN 7a

Reported uncertainties in the U-trend dates used in the calibration curve may not accurately represent the error associated with these dates. Rosholt et al. (1985) report that gravels in unit Q2c "overlie and contain reworked cinders" from the Lathrop Wells volcano, which has an estimated age of 0.1±0.05 Ma. However, unit Q2c has a U-trend date of 255±15 ka (Harrington and Whitney, 1987), and older dates for this unit are reported in Rosholt et al. (1985). The large uncertainties in the accuracy and precision of the U-trend dates need to be accurately incorporated in the calibration curve.

CONCERN 8

Uncertainties for individual VCR analyses must be reported in order to assess the contribution of analytical error to VCR variations within and between samples.

CONCERN 9

The calibration curve used to calculate cation-ratio dates does not adequately represent the uncertainty associated with the data used to construct the curve.

CONCERN 10

The basis for selecting dates of 1.12±0.07 Ma for Red Cone and 1.1±0.3 Ma for Black Cone varnishes used in the calibration curve is not clear because multiple dates of varying precision and accuracy are available for these volcanoes. The 1.12±0.07 Ma date for Red Cone is not reported in the references cited by Harrington and Whitney (1987), whereas reported dates for this volcano range from 1.8±0.2 to 0.95±0.11 Ma (Sinnock and Easterling, 1983).

CONCERN 11

Why are the error bars for the VCRs in the calibration curve in the TR roughly 75 percent smaller than reported in the original reference (Harrington and Whitney, 1987), when apparently identical analytical methods were used?

CONCERN 12

The basis for using the standardless semiquantitative (SSQ) program for VCR analyses needs to be explained because this program may not accurately determine Ti abundances in the presence of Ba. How was the Ti correction for these inadequacies derived, especially in light of the significance of Ba in determining VCR values (Harrington et al., 1991)? Has the correction to the SSQ-generated data also been applied to the calibration data?

CONCERN 13

It is not apparent criteria were used to apparently discard selected VCR analyses from each sample set. In the data from the boulder deposits there are sometimes 7, 8, or 9 analytical sites on single disks (even taking into account that there are sometimes multiple readings at different keVs at single sites). Why were more than six disk sites analyzed? Why, in some instances, were as many as 40 percent of the readings rejected?

CONCERN 14

In the raw VCR data for the 12 boulder-mantled geomorphic surfaces there appear to be considerably more data sets (readings from individual disks/boulders) than are referred to in the TR (Table 4). Please clarify: (i) which data were used to obtain the mean VCR's presented in the TR (and in Harrington and Whitney, 1993) and (ii) why some data were discarded.

CONCERN 14a

The method used to calculate uncertainty in the VCRs dates does not accurately reflect the large variations in the data set. The standard deviation of the VCR population for an entire deposit will provide a more accurate estimate of VCR uncertainty than the standard deviation of the average values for the sample disks. In addition, the confidence interval methodology of Bierman et al. (1991) used to estimate VCR uncertainty is only appropriate for sample populations with error normally distributed about the mean. Given that the sampling and analytical methods in this study are extremely biased towards non-random sampling of a population, it is not clear how the uncertainties calculated after Bierman et al. (1991) are defendable.

CONCERN 15

Hooke and Dorn (1992) state that several VCR ages of greater than 250 ka from Death Valley "are near the limits of usefulness of the ... technique" and may have uncertainties in excess of 100 ka. This observation must be applied to the VCR dates presented in the TR.

3. THE QUALIFICATION OF EXISTING DATA ON EROSION

CONCERN 16

The Peer Review Group (Birkeland, et al., 1989) indicated that more VCR calibration points were required and that additional absolute dating methods should be used (i.e., other than U-trend analyses of the Crater Flat and Fortymile Wash alluvial terraces). This has not been done. The present VCR calibration curve has no more data than that originally published by Harrington and Whitney (1987).

CONCERN 17

The Peer Review Group Birkeland, et al, (1989) also suggested that there should be a check on the procedure for determining that the SEM-EDS data truly represent the VCR data from the basal varnish layer and that substrate (host rock) is not interfering with the VCR determination. There is no information in the TR to indicate that this suggestion has been incorporated in the current analysis. In some cases different keVs (15, 20, 25, and 30) are used to obtain a cation ratio "profile" at one disk site. The lowest VCR reading is used in the calculations of the mean VCR. On some disks, however, only one keV is used (for example, see samples from YMW-2). How can one be certain that even lower cation-ratios are not present? In some instances, the lowest VCR readings on a single disk or individual boulder occur at different keVs (for example, see YMW-1 sample identification WYM-03) but sometimes only one reading will be taken at some of the other sites on the same disk. This leads to the possibility that still lower VCRs may be present. Clearly, this would lower the mean VCR for the disk, boulder, and geomorphic surface; however, it might also increase the standard deviation about the mean, thereby increasing the level of uncertainty.

4. COMPREHENSIVENESS OF THE DATA SUBMITTED

CONCERN 18

Although the development and issuance of a geomorphic map of Yucca Mountain is an important factor in the analysis for the evaluation and determination of the presence, or absence, of geomorphic processes such as extreme erosion, apparently no such map has been prepared by the DOE and submitted with the TR.

CONCERN 19

Why does the TR include no "data" supporting the amount of landscape change?

CONCERN 20

The raw VCR data for the Red Cone/Black Cone data points used on the calibration curve have not been provided. These data were assumed to have been included (but were not) with the data packages requested in NRC's TR Acceptance Review letter of October 15, 1993 (Joseph J. Holonich, NRC, to Dwight E. Shelor, DOE).

CONCERN 21

Reneau et al. (1992) conclude that the initial composition of rock varnish controls VCRs and that Ca and K may not be preferentially leached out of varnish minerals. This hypothesis is based on variations in Ca, K, and Ti relative to Si, Mn, and Fe. Harrington and Whitney (1987) report that some varnish samples were analyzed for Si, Al, Fe, Mn, Mg, P, and S in addition to Ca, K, and Ti. These analyses should be provided in order to evaluate the hypothesis of Reneau et al. (1992).

APPENDIX D

COMMENTS ON THE DOE/NRC FIELD TRIP TO YUCCA MOUNTAIN, NEVADA AND VICINITY ON FEBRUARY 1 AND 2, 1994

OBJECTIVES

The main goal of the field trip was to discuss with the DOE the list of concerns raised by the NRC/CNWRA relative to the DOE Topical Report (TR) "Evaluation of the Potentially Adverse Condition 'Evidence For Extreme Erosion During the Quaternary Period' At Yucca Mountain, Nevada." The site visit provided an opportunity to examine the varnished deposits which are the focus of most of the work presented in the TR. Furthermore, the broader geomorphological context of the site could be addressed and the ramifications of the study's conclusions evaluated. Attachment D-1 is the itinerary of the DOE-led field trip.

SCOPE OF THE FIELD TRIP

Because the bulk of the TR deals with varnished hillslope boulder deposits and their potential for providing the ages of stable geomorphic surfaces with which they are suggested to be associated, much of the field trip involved viewing several of the dated deposits and discussing their geomorphic and paleoenvironmental context. In addition, DOE investigators showed the participants other geomorphic and pedological features which provided supplementary corroborating evidence concerning the area's environmental history. At these additional sites, trenches exposing well-developed calcretes, recent hillslope debris flows, Holocene(?) alluvium, and other Quaternary sedimentary features were observed and their relevance to extreme erosion discussed.

RESULTS

The two-day field trip was very helpful and informative. All but two of the NRC/CNWRA concerns with the TR, raised in the list submitted informally to the DOE (i.e., Appendix C), were addressed by the investigators. In addition, a number of other comments which were raised in the CNWRA comments on the annotated outline for the TR were discussed. The nature of the investigator's responses to the concerns and other pertinent questions raised by the NRC/CNWRA staff and other interested parties varied considerable. Some issues were essentially resolved in the field although the fact that the questions surfaced from an analysis of the TR indicates that additional explanation in a revised TR is required to clarify the particular concerns for any reader of the TR. For example, the use of the SSQ-program to determine cation-ratios despite its apparent inadequacies was satisfactorily explained by Dr. Harrington. This explanation must be a part of the revised TR in view of the published shortcomings of the program (Harrington et al., 1991).

The response of the DOE to other concerns raised additional questions which have not been addressed in the TR or in the NRC/CNWRA comments on the annotated outline for the TR. For example, it was stated by Dr. Harrington that new evidence suggests that the SEM-EDS analysis of varnish may provide cation-ratio data for perhaps only the upper 10 μm of the varnish coatings. If this surmise is true, it has profound implications on the understanding of the reason why older varnishes appear to have lower varnish cation-ratios (VCRs) than younger varnishes. The idea that the outermost (youngest?) portion of an accretionary surface would provide the oldest age measurement is to say the least revolutionary. At present this issue of only measuring the uppermost 10 μm of a desert varnish is not broached in the TR.

Similarly, certain assumptions about the nature of early and mid-Pleistocene paleoclimates are required to substantiate the proposed origin of the hillslope boulder deposits. The investigators have suggested that there is some local evidence to corroborate their interpretation. This corroborative evidence is not presented in the TR. Moreover, the broader significance and causes of an apparently unique paleoenvironmental history for the region (one which is very different from elsewhere in North America, and the rest of the globe) must be defended in the TR.

Some concerns raised by the NRC, both in writing and during the site visit, and certain comments in the NRC evaluation of the annotated outline of the TR, were not addressed by the DOE investigators. Apparent inconsistencies in the sampling, analytical procedures, and data selection were not thoroughly explained. Part of the problem in these discussions originated because the Principal Investigators for the DOE had never seen the format of the data in the DOE database. Additionally, some fundamental errors in the VCR data analysis (particularly the statistical treatment of the VCR data) pointed out by the NRC/CNWRA were not fully acknowledged.

The two issues which were raised by the NRC/CNWRA but which were not discussed during the course of the field trip were:

- In the discussion of erosion rates in similar dry, semi-arid to arid environments, the TR does not address the issue of local relief. Local relief can be an overriding influence on rates of regional denudation and more localized and extreme erosion. The comparison in the TR of areas with similar climate or bedrock but with different local relief may be invalid.

- Possible problems associated with the use of cation-ratio data from varnishes on two lithologically different substrates to construct the calibration curve for Yucca Mountain. Comparing cation-ratios on different substrates may totally skew the resultant calibration curve inappropriately resulting in erroneous ages being assigned to VCRs.

DISCUSSION

The information obtained during the DOE-sponsored field trip as well as additional field excursions sponsored by Nye County and the NRC/CNWRA field days at Yucca Mountain, Nevada and in Death Valley, California raised several additional issues related to the presence of extreme erosion during the Quaternary Period at Yucca Mountain, Nevada. The discussion below elucidates these important issues.

Extent and Location of Boulder Deposits

The colluvial boulder deposits, on which the entire premise of the absence of extreme erosion at the proposed repository site is based, probably cover less than 10 percent of the hillslope surfaces in the vicinity of Yucca Mountain, Nevada (based on an estimate by Whitney given verbally during the DOE field trip). It would seem that the value of the boulder deposits as indicators of universal landscape stability is very limited. During the course of the DOE trip it was argued that the presence of ancient hillslope boulder deposits does indeed indicate stability of the entire landscape. It was also stated by DOE investigators that in nearby Death Valley (which experiences some of the highest current rates of erosion and sedimentation in North America) there are no old, stable surfaces. During a visit to Hanaupah Fan, on the west side of Death Valley, NRC/CNWRA personnel identified what appeared to be (from afar) varnished boulders deposits on the hillslopes above the fan. This particular fan has recently been studied by Hooke and Dorn (1992) and is thought to exhibit both ancient (greater than 500 kabp) and recent (Holocene, 10 kabp) fan deposits. Apparently, possibly relict hillslope boulder deposits can be preserved locally in areas of very high geomorphic activity. This contradicts statements and assumptions of DOE investigators for Yucca Mountain, Nevada.

Verification of Boulder Deposit Antiquity Using Interbedded Materials

The varnished boulder deposits found on Yucca Mountain and neighboring hillslopes rarely occur in any clear stratigraphic context with other datable sediments or soils. This fact severely constrains the ability to use other geomorphic and pedologic information to corroborate the ages of the hillslope deposits. However, in those rare cases where either boulder deposits themselves or the materials eroded from the gullies adjacent to the boulder deposits are interbedded with other deposits at the foot of the hillslopes the proposed chronology of the geomorphic events could be better constrained. Such evidence could provide strong corroboration for the proposed antiquity of the boulder deposits but is nowhere presented in the TR. During the site visit, the DOE investigators asserted that neither Fortymile Wash nor the eastern portion of the Crater Flat drainage catchment contain significant amounts of sediments of Holocene age. If this assertion can be demonstrated, it would provide very strong evidence of low rates of erosion within these affected basins. This type of information, when presented in conjunction with a map showing the primary geomorphological features of the area, might provide more appropriate, defensible, acceptable evidence of general landscape stability than do the few isolated hillslope boulder deposits which are the current focus of the TR.

Verifying Antiquity of Boulder Deposits Using Tephras and Aeolian Sands

Several examples of Pleistocene tephras and eolian sand and silt deposits were identified during the course of the DOE field trip. Additional samples were identified and discussed in the vicinity of paleo lake Tecopa by investigators for Nye County. Investigation of the possibility that antiquity of boulder deposits could be corroborated by identifying such tephras and identifiable eolian sand and silt deposits within the boulder deposits should occur. If, as the DOE investigators insist, the boulder deposits are very efficient traps of atmospheric dust it would seem that some relict, identifiable tephras, or other datable materials might be found in boulder interstices.

Paleoclimate Interpretation

The paleoclimate interpretation in the TR concerning the origin of the hillslope boulder deposits remains unclear and potentially controversial. Using the Buckboard Mesa boulder deposit as an example, its purported origin would be as a talus slope formed during a cold, and probably wet, climate occurring at about 1.5 Mabp. After formation of the boulder blocks, varnish began to form on the boulders influenced by somewhat drier climatic conditions. Subsequently, one or more additional cold periods created the bouldery talus on other nearby hillslopes (e.g., Yucca Mountain itself, which has boulder deposits dated about 1 Ma younger than Buckboard Mesa). The DOE must explain why the older varnished talus at Buckboard Mesa remained stable while new boulder blocks were being developed at Yucca Mountain, and why the varnish at Buckboard Mesa was preserved during the recent cold phases which initiated the Yucca Mountain Boulder deposits.

The overall issue of late (terminal) Pleistocene climatic conditions must be addressed in a global context. It is widely accepted that the LGM exhibited the lowest (coolest) temperatures during the entire Quaternary Period. This temperature decline applies not only to the glaciated regions temperature but also to the subtropical, tropical, and equatorial regions of the earth.

The DOE must explain how it is possible to account for several severely cold phases in the early and mid-Pleistocene at Yucca Mountain, Nevada while, no similar climatic incidents are recorded at Yucca Mountain for the LGM.

Alternate Scenario to Establish Rock Varnish Calibration Curve Ages

In the light of the foregoing comments regarding the apparent inconsistencies in the paleoenvironmental interpretation of the hillslope boulder deposits, and also the possible errors resulting from combining VCR data from lithologically different host rocks, a radically different assessment can be proposed. This alternate scenario proposes that the antiquity ascribed to the samples used in the construction of the calibration curve does not necessarily represent the time at which the varnish began to form on the clasts. Rather, the ages are those of the host rock (the basalts at Red Cone or Black Cone) or soil materials in the case of the samples from alluvial surfaces of Crater Flat and Fortymile Wash. If this is so, one could assume that all the varnish has formed during the past 200 ka or less. In such a scenario, the distinction in the VCRs for the two older alluvial clasts and the Black and Red cone samples might result merely from the difference in the substrate. Moreover, the differences in the VCRs between most of the older dated samples may not be significant when both analytical error and the true statistical variance are taken into account.

The validity of such an alternative could be readily tested by: (i) Calculating the true error and uncertainty in the VCR data, and (ii) Comparing the VCR readings from clasts of different lithology on the same geomorphological surface, for example, from selected clasts on the Crater Flat alluvial fan.

CONCLUSIONS

During the course of the site visit the following became apparent:

- Hillslope boulder deposits are neither very extensive, nor useful indicators of normal or extreme geomorphic conditions in the study area

- VCR dating technique is poorly understood and remains controversial (see Bierman and Gillespie, 1994).

Additionally, the DOE investigators demonstrated that there are a number of other sources of geomorphologic and paleoenvironmental information in the region and at the site which are potentially pertinent to an understanding of the presence of evidence of extreme erosion at the Yucca Mountain proposed repository. The TR does not contain all of the available data and appropriate discussion which was presented during the course of the DOE-sponsored field visit. While some of this new data is still in the process of being collected, assessed, and reviewed, it seems likely that a broader approach to the discussion of extreme erosion in the TR would provide a more coherent, defensible argument for the DOE position regarding the absence of the extreme erosion potentially adverse condition. Of particular significance are new data pertaining to ancient calcic soils beneath boulder deposits and on lower hillslopes; the ages of paleosols in sand ramp deposits in juxtapositions with boulder deposits and elsewhere; the stratigraphic relationship between boulder deposits and other reliably datable sediments and materials; and the sedimentologic history of Crater Flat and Fortymile Wash.

Attachment D-1

ITINERARY FOR DOE-NRC SITE VISIT FOR EROSION TOPICAL REPORT TOPICS
NEVADA TEST SITE (NTS) AND ENVIRONS
FEBRUARY 1-2, 1994

FEBRUARY 1, 1994

6:00 Depart Beatty

6:35 Arrive at Steve's Pass for overview of visit
- Introduction of trip organizers and opening remarks

7:00 Depart for Solitario Canyon through Crater Flat

7:45 Solitario Canyon to visit and discuss
- Oldest dated boulder deposit on west slope of Yucca Mountain (YMW-3); Reference Figure 4 of Topical Report (TR) [requires 1 to 1.5 hour hike from vehicles to deposit and back; moderately strenuous]

10:45 Drive to Trench through Solitario Canyon Fault (SCFT-2)

11:05 Discuss thick carbonate deposits and pediment surface at SCFT-1 (also carbonate deposits and pediment surface; if time allows)

11:45 Drive to Trench CF-1

11:55 Discuss exposure of alluvium at CF-1

12:15 Drive to NTS Gate 510, via Steve's Pass [LUNCH will be during drive to Gate 510 or as opportunity allows]

1:00 Badging at NTS Gate 510

1:15 Drive to Field Operations Center (FOC)

1:30 Break at FOC

1:45 Drive to Yucca Mountain

2:15 East Flank of Yucca Mountain to visit and discuss:
- Hillslope boulder deposits on Boundary Ridge (YME-2); Reference Figure 5 of TR
2:50 - Hillslope boulder deposit at head of Abandon Wash (YME-1); Reference Figures 3 and 5 of TR; 1 hour hike to deposit and back

4:15 Discussion of Sand Ramp history in area

4:30 Return to Beatty (or Mercury, as required)

Attachment 4 (continued)

ITINERARY FOR DOE-NRC SITE VISIT FOR EROSION TOPICAL REPORT TOPICS
NEVADA TEST SITE (NTS) AND ENVIRONS
FEBRUARY 1-2, 1994

FEBRUARY 2, 1994

5:45 AM	Leave Beatty, NV for Skull Mountain via Gate 510
7:00	Skull Mountain SKM-1 and SKM-3 overview of varnish deposits from road; Reference Figure 6 in TR
7:30	Drive to Little Skull Mountain
7:40	Little Skull Mountain Pass to visit and discuss cross-section of hillslope colluvial boulder deposit (LSM-1); Reference Figure 5 of TR
8:20	Drive to Fortymile Wash vista
8:40	Fortymile Wash to discuss Tertiary and Quaternary geologic history
8:55	Drive to Fortymile Wash rim
9:05	Fortymile Wash to discuss Tertiary and Quaternary geologic history [10 minute walk]; Reference Figure 13 in TR
9:50	Drive to Coyote Wash
10:00	Coyote Wash to visit and discuss canyon cutting and Holocene geologic history
10:50	Drive to Jake Ridge
11:15	Jake Ridge to visit and discuss 1984 erosion event and role of infrequent erosion events on landscape
11:45	Drive to Buckboard Mesa [Lunch will be eaten during drive to Buckboard Mesa or as opportunity allows]
1:20 PM	Buckboard Mesa to visit and discuss oldest dated hillslope colluvial boulder deposits in Yucca Mountain area (BM-1) and upper Fortymile Canyon history (1 hour hike to deposit and back); Reference Figures 5 and 10 from TR
3:20	Depart for wrap-up session in Mercury
4:10	Wrap-up session in Mercury cafeteria - NRC provide discussion/overview of their comments from review of TR - Questions and comments from state and affected counties - DOE closing remarks
5:10	Depart for Mercury Gate 100; return NTS badges, return to Las Vegas or Beatty, NV