A0297

Potential Erosion at the Yucca Mountain Nuclear Waste Site*

by

Charles (Rus) Purcell

Submitted to

Lawrence Livermore National Laboratory, Livermore, California

(Dae H. Chung, Program Manager)

*This work was supported by the U. S. Nuclear Regulatory Commission through the Lawrence Livermore National Laboratory (FIN A0297).

September 1986

TABLE OF CONTENTS

LIST OF TABLE

Table Number

INTRODUCTION

This report on expected rates of erosion in the Yucca Mountain region as a result of future climatic changes in the arid and semiarid southwest, is in response to a letter of authorization dated March 5, 1985 from the Nuclear Regulatory Commission.

This report is intended to be a short review and analysis of the current literature pertaining to the titled subject, and is based on the most recent and readily available data. No primary data were collected. This report is not intended to be a guideline on erosion hazards and should not be applied for such purposes.

The Background section presents data on paleoclimate of the desert areas of the southwestern United States and erosion studies pertinent to arid-semiarid regions. The section on Erosion Potential at the Nevada Test Site (NTS) discusses the applicability of the background climatic and erosion data to the proposed Yucca Mountain site, evaluates the existing data at the site, and recommends future work necessary to complete the assessment of erosion potential for Yucca Mountain. The report concludes with a brief Summary and a section of References.

BACKGROUND

Paleoclimate

Paleoclimate reconstruction has been an important area of interest in the geologic, biologic, and ecologic sciences for years. Various types of approaches to estimating changes in past climates have been used. These include evaluations based on hydrologic budgets, macrofossils, cryogenic deposits, and snow line changes to list a few. From these various approaches come predictions of past climates, mostly in the Quaternary and to a lesser extent into the late Tertiary. As would be expected, the degree of compatibility of the various studies is small. For this paper we will concentrate on the paleoclimate estimated on primarily full glacial and pluvial times, as this should represent the time of maximum conditions in the past and can best be used to project maximum future conditions.

As previously stated, this report is not intended to be all inclusive but will present a range of possible paleoclimatic scenarios applicable to the NTS. For detailed listings and discussions of past background studies on paleoclimate refer to the appropriate sections of Mifflin and Wheat (1979), Spaulding (1983), Spaulding and others (1984), Wells and others (1984), and Winograd (1980).

A few selected examples of paleoclimate reconstructions are presented here to support the conclusions of this report. Mifflin nd Wheat (1979), in their work on pluvial lakes and pluvial climates estimated that full pluvial climates were not much different than today and predict a sufficient increase in precipitation could be brought about by lower mean annual temperature no more than 3° C. Bradley (1985) agrees that the modern climate is closer to full glacial climate than interglacial times and calls for little or no increase in precipitation with cooler temperatures for the Great Basin. Spaulding (1983) and Mifflin and Wheat (1979) both suggest that modern climates in northern Nevada approximate the pluvial climate conditions in south-central Nevada. Winograd (1980) predicts on a basis of hydrologic studies that the climate was significantly wetter during the Pleistocene, especially between about 10,000 to 40,000 years ago, from some combination of increased precipitation and decreased temperature. Expanding into more recent time periods, Cole and Webb (1985) and LaMarche (1973) suggest a cooler and sometimes wetter climate in the late Holocene. Spaulding (1983) in his work on macrofossils (packrat middens) has described the climate of the last 45,000 years as follows: The climate 45,000 years ago is similar to today's climate in northern Nevada, with average annual temperatures about 2° C less than today. Average annual temperatures 18,000 years ago were about 6-7° C less than today with summer temperatures 7-8° C lower and winter precipitation 70% greater. However, this still leads to an average annual precipitation rate of about 40% greater than present conditions.

Although Spaulding (1983) and Mifflin and Wheat (1979) are in basic agreement on the pluvial climate of south-central Nevada being similar to modern northern Nevada, their climatic reconstructions differ significantly with overall change in mean annual temperature and precipitation. Mifflin and Wheat (1979) estimated a temperature change of about 3° C and increase mean annual precipitation of about 70%. Spaulding (1983) estimated a 6-7° C increase in temperature and an increase in mean annual precipitation of no more than 40%.

From this comparison it becomes obvious that a wide range of paleoclimate reconstructions exist. Mifflin and Wheat (1979) reviewed 27 references on pluvial climates and noted that only two of those references called for less than a 3° C decrease in temperature while all the others called for changes in temperature greater than 5-6 °C.

Ranges from the literature predict mean annual temperature changes from 2° C (Van Devender, 1973) to 11° C (Galloway, 1970, 1983). Associated with the range of mean annual temperatures is the estimated range of increase of mean annual precipitation from 0.0 mm (Brackenridge, 1978) to 250.0 mm (Leopold, 1951) an estimates of from ~20% (Galloway, 1979, 1983) to 100% (Antevs, 1952) of present precipitation.

Spaulding and others (1984) have divided the many studies of paleoclimatic reconstruction into three basic types of pluvial climates: 1) mild-pluvial, 2) cold-dry, and 3) cold-pluvial (Table 1). Further variations have also been interpreted between the maximum pluvial climate and the present climatic conditions. For example, Morrison (1964) suggests there is evidence, primarily based on paleopedologic data, suggestive of not only cool-most periods but cool-dry and warm-moist conditions.

All the listed paleoclimate reconstructions are based on climatic response to the volume of polar ice. Recently, based on his work in Searles Lake and the marine oxygen isotope record, Smith (1984) has suggested that some sort of global phenomena is responsible for climatic changes but not necessarily phenomena that systematically affected the volume of polar ice. He suggests that the 413,000 year orbital eccentricity cycle may cause cyclical variations in global temperatures that could be partly expressed by changes in surface temperature in all oceans and that these cycles influence the amount of precipitation reaching mid-latitude areas.

Whatever theory is preferred is presently unimportant. The importance of the paleoclimate reconstructions is that whatever the specifics, there is agreement that a higher effective moisture was present in late glacial, pluvial, and Holocene time (Wells and others, 1984).

Erosion

Estimates of potential erosion at a specific location or site must consider a large number of variables. Included in this list of variables are climate (temperature and precipitation), vegetation cover, slope, type of surface material, baselevel factors (uplift and/or subsidence), and the effects of man in the area of concern. The literature pertinent to the subject covers two basic types of studies, erosion/denudation/degradation rates, and deformation and uplift rates. This report treats the terms erosion, denudation, and degradation as synonyms and interchanges the terms based on the reference material being discussed. When basically unreferenced data is discussed, erosion will be used.

Table 1 Paleoclimatic reconstruction for the Wisconsin maximum in the American west. (After Spaulding and others, 1984)

[$-\Delta T_a$, change, in degrees Celsius, in annual temperatures; $-\Delta T_s$, change, in degrees Celsius, in summer temperatures; $-\Delta T_w$, change in degrees Celsius, in winter temperature; ΔP, change, in millimeters (mm), in annual precipitation; percent P, ΔP/modern P x 100]

Reference	Study area	Methods	$-\Delta T_a$	$-\Delta T_s$	$-\Delta T_w$	ΔP (mm)	Percent P
			Mild-pluvial reconstructions				
Antevs, 1952	Lake Lahontan, Nevada	Hydrologic budgets	2.5 to 3	–	–	+80 to +160	+50 to +100
Broecker and Orr, 1958	Lake Lahontan, Nevada	Hydrologic budgets	5	–	–	+200	+80
Mifflin and Wheat, 1979	Nevada, state-wide	Hydrologic budgets	3	–	–	–	[1]+68
Snyder and Langbein, 1962.	Spring Valley, Nevada	Hydrologic budgets	[2]5	[3]7.2	–	+200	+67
Van Devender, 1973	Western Arizona	Packrat middens	2 to 4	–	–	+120 to +220	–
			Cold-dry reconstructions				
Brakenridge, 1978	Montana to Arizona (lat 45°40' N. to 33°22' N.).	Relict cirques and cryogenic deposits	[4]8	8	–	0	0
Galloway, 1970, 1983	Southwestern United States	Cryogenic deposits	10 to 11	–	–	–	–20
			Cold-pluvial reconstructions				
Leopold, 1951	Lake Estancia, New Mexico	Hydrologic budgets and snow line changes	6.6	9	2.8	+180 to +250	+50 to +70
Spaulding, 1983a	Southern Great	Packrat middens	6 to 7	7 to 8	[5]6	–	+30 to +40

[1]State wide average.
[2]Extrapolated by Morrison (1965) and Schumm (1965).
[3]Extrapolated by Schumm (1965) and Brakenridge (1978).
[4]Recalculated by Smith and Street-Perrott (1983).
[5]Minimum estimate.

Winograd (1974) summarized the literature on denudation and slope retreat rates in arid and semiarid climates. His average rate is 9-18 cm/1000 yr. Dohrenwend and others (1984) have reported average degradation rates in their work in the Cima Volcanic Field in the Mojave Desert. Their rates are based on the relation between the average pediment high above the modern surface and the K-Ar age of the basalt flow capping that remnant pediment. Degradation rates range from 0.9 to 4.6 cm/1000 yr. at the Cima Volcanic field (Table 2). This data gives an average denudation rate of about 2.1 cm/1000 yr. and is basically applicable over the last 4 million years. For contrast, the Cima rates were compared to published erosion rates for other areas. The data at the Cima field basically are very similar to rates presented by Hamblin and others (1981) for the western margin of the Colorado Plateau (2.5 cm/1000 yr.). The Cima denudation rates are about 2 to 4 times less than rates at the tectonically active area along the Hurricane Fault (Hamblin and others, 1981) while they are 2 to 10 times greater than rates reported for the tectonically quiet area on the east flank of the Great Dividing range in New South wales, Australia (Young, 1983). In contrast to the rates of pediment degradation, Dohrenwend and others (1984) also noted canyon downcutting in localized areas capped by lava flows has proceeded at rates as high as 20 cm/1000 yr.; nearly an order of magnitude greater than the pediment areas (Figure 1).

Another study by Dohrenwend and others (1985) estimates erosion rates for different parts of the erosion system on the Revielle Range, Nye County, Nevada. He estimates erosion rates based on comparison of paleosurfaces separated by K-Ar dated basalt flows and finds: 1) maximum erosion in upper reaches (i.e., crestal and upper flank areas) and approximate equilibrium in midpiedmont regions and 2) accelerated erosion during early phases of range dissection followed by less erosion during later phases. Erosion rates in the upper reaches range from 1.6 to 3.1 cm/1000 yr. In the lower flank and upper piedmont reaches, the erosion rates range from 5.8 cm/1000 yr. (from 5.9 to 3.8 myBP) to 1.6 cm/1000 yr. (since 3.9 myBP), while the central and lower piedmont reaches are essentially undissected. Damon and others (1978) estimate an erosion rate around 0.4 cm/1000 yr. for areas of the lower Colorado River for the last 3.8 myBP.

Schumm and Chorley (1983) have compiled an excellent document on the role of geomorphic hazards, including erosion, and their application to the management of nuclear waste. In this document they discuss some general changes, rates of valley incision,

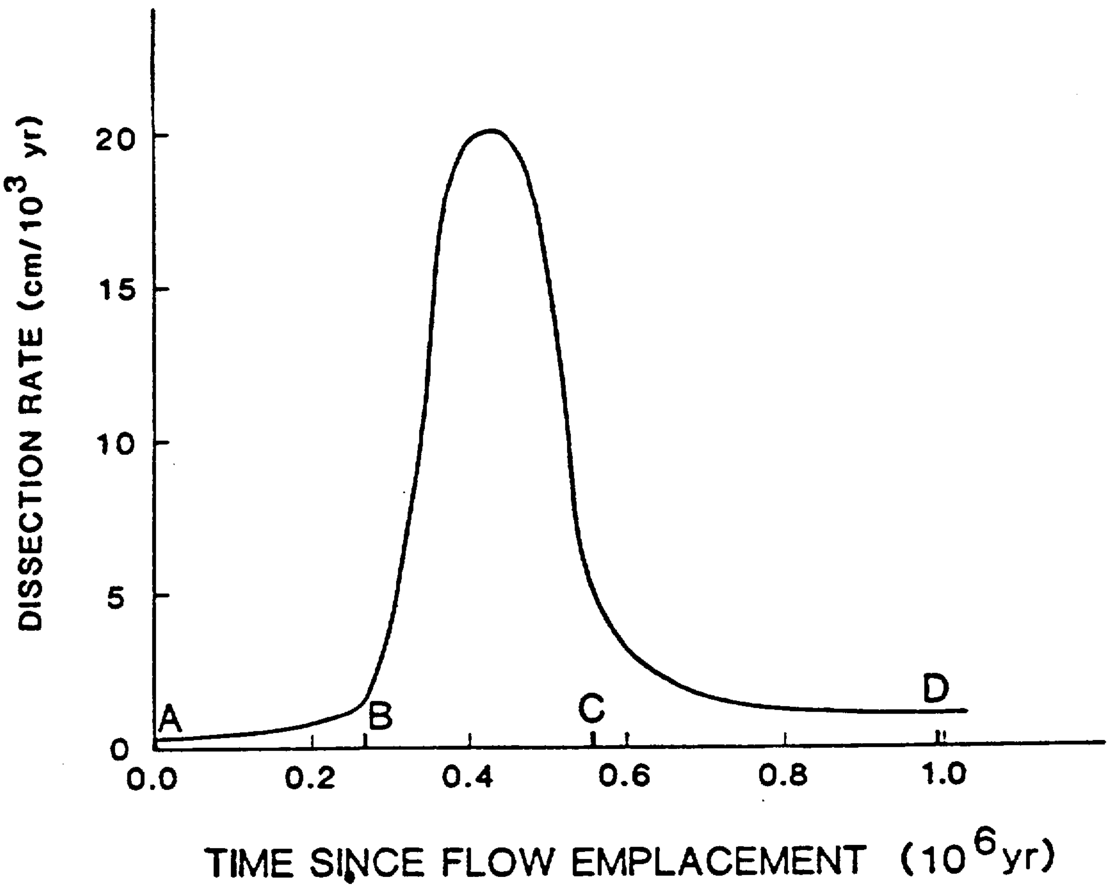
Table 2 Downwasting rates in the Cima volcanic field.

Flow Designation	Flow Age (m.y.)[1]	Maximum Height Above Modern Surface (m)	Approximate Downwasting Rate (ca/10^3 yr)
z_1	0.27 ± 0.11	6.5	2.4
t_2	0.27 ± 0.05	6.6	2.5
j'_1	0.33 ± 0.03	4.0	1.2
m_3	0.39 ± 0.08	3.5	0.9
s_x	0.58 ± 0.16	12	2.1
s_2	0.64 ± 0.05	17	2.6
		11 (t_2)[b]	3.0[2]
x_3	0.67 ± 0.13	18	2.7
		10.5(x_1)[c]	2.6[3]
r_2	0.70 ± 0.06	32	4.6
r_3	0.85 ± 0.05	25	2.9
k_3	0.99 ± 0.07	19	1.9
Tv	3.88 ± 0.09	120	3.1

(from Dohrenwend and others, 1984)

[1]Radiometric ages from Turrin et al. (this volume); ± values are 2 sigma error ranges.
[2]Difference in height between the base of flow s_2 and the base of flow t_2; dissection rate for the period 0.64 to 0.27 m.y.
[3]Difference in height between the base of flow x_3 and the base of flow x_1; dissection rate for the period 0.67 to 0.27 m.y.

Figure 1 Canyon development through time.



Canyon development through time in areas capped by lava flows. Canyons have been formed by relatively rapid and short-lived pulses of erosion. After emplacement of the lava flows (time A), little dissection occurs for at least 0.2 to 0.3 m.y. Canyon cutting then proceeds at rates ten to twenty times greater than average pediment downwasting rates (time B to time C). As equilibrium is approached (time C), dissection rates drop precipitously to the average downwasting rate of the surrounding pediment. Time D = 1984.

(from Dohrenwend and others, 1984)

hillslope erosion, and escarpment retreat. Although none of their examples directly covers the NTS area, important relationships are summarized.

Table 3 is a general compilation of regional denudation rates throughout the world. These estimates range from 1.6 cm/1000 yr. on the Thames River to 100 cm/1000 yr. in the Himalayas, basically demonstrating the large range of active rates.

Schumm and Chorley 9183) discuss the differences and uniqueness of valley incision, hillslope erosion and escarpment retreat. These three separate aspects play a cumulative role, when combined with uplift rates and sediment yield data, in the total evaluation of the potential erosion at a specific site. Valley incision rates, based on rock types and location, range from 2.6 cm/1000 yr. on limestone and basalt in Utah to 30 cm/1000 yr. on sedimentary rocks in Colorado (Table 4). Hillslope erosion rates, based on climate, range from a low of 200 cm/ 1000 yr. to a high of 820 cm/ 1000 yr. in semiarid regions (Table 5). This process of hillslope erosion uses water as its dominant agent and is dependent on sheetwash and rill erosion, slope angle and length, inherent soil erodibility, vegetation cover, and surface management practices. Typical estimates of hillslope erosion are made by applying the Universal Soil Loss Equation (USLE). This equation was developed primarily for croplands in the midwest but modifications to the equation have helped expand its geographic applicability. Still, great care is necessary in determining the equation parameters for an arid to semiarid environment. Refer to U.S. Department of Agriculture (1977) for an expanded discussion of the USLE in the midwest states. Rates of scarp or escarpment retreat, based on rock type and climate, range from 20 cm/ 1000 yr. for sandstone in a semiarid climate to 200 to 1300 cm/1000 yr. for shales in a semiarid climate (Table 6). Escarpment retreat is primarily a function of mechanical weathering and rock type.

Tectonic activity, uplift and/or subsidence effect erosion rates by changing baselevels. Uplift is typically rapid and of short duration allowing for little erosion. However, situations do exist where the rates of uplift and erosion are nearly equal. Not only are uplift rates important in assessing erosion potential, but the type of uplift may have a distinct effect on where or how the responding erosion takes place. For example, tilting will increase erosion throughout the tilted region while near vertical uplift will concentrate incision along the margins of the uplifted area.

Table 3 Regional denudation rate.

Region	Present Denudation Rate (mm/100 yrs) mean	range
Himalayas	1000	
N. Alps	610	
French & Swiss Alps	379	287-518
Colorado River	165	58-
Utah	130	82-177
Hawaii	130	
California	81	
W. Gulf (Texas)	53	16-
Mississippi River	51	
S.E. U.S.A.	41	28-
N.E. U.S.A.	38	27-48
Columbia River	38	
Thames River	16	

(from Schumm and Chorley, 1983)

Table 4 Rates of valley incision.

Rate (mm/1000 yrs)	Rock Type	Location	Source
240	granite	SE Australia	Brittlebank, 1900
96	basalt	SE Australia	Brittlebank, 1900
95	conglomerate	Arizona	Rice, 1980
248	shale	Arizona	Rice, 1980
300	sedimentary rock	Colorado	Larsen et al., 1975
70	metamorphic rock	Colorado	Scott, 1975
370	limestone and basalt	Utah	Hamblin et al., 1981
26	limestone and basalt	Utah	
87		Sierra Nevada, CA	Huber, 1981

(from Schumm and Chorley, 1983)

Table 5 Rates of hillslope erosion.

Climate	Ground Lowering mm/yr	Volumetric Movement, cm^3/cm/yr
Temperate	–	0.08
Temperate	0.005	–
Temperate	0.005	–
Temperate	0.03	–
Temperate	–	0.08
Temperate	0.01–0.06	–
Temperate montane	0.01	–
Warm temperate	0.05–0.10	–
Mediterranean	0.09	–
Semi-arid	2.0	
Semi-arid	6.40-8.20	–
Savanna	0.039*	–
Rainforest	5.0-15.0	–

(from Schumm and Chorley, 1983)

Table 6 Rates of scarp retreat.

Rock Type	Climate	Recession mm/yr
Shale	Semiarid	2 - 13
Granite, Gneiss	Rainforest	2 - 20
Sandstone	Humid Temperature	0.5
Sandstone	Semiarid/Arid	0.6
Sandstone	Semiarid/Arid	0.2

(from Schumm and Chorley, 1983)

Carr (1984) suggests uplift rates from 1 cm/1000 yr near Crater Flat to 180 cm/1000 yr at the Coso Range in California. Winograd (1980) presents uplift rates from 10 to 40 cm/1000 yr. and favors the lower end of the range for the NTS area. Gable and Hatton (1980) present uplift rates of 20 to 60 cm/1000 yr. increasing southwestwardly across the NTS. Carr (1984) suggests Gable and Hatton's data is much too high for the HTS area and discusses his reasons as well as presenting data on approximate rates of relative vertical tectonic adjustment of burial in the SW Great Basin during the late Neogene and Quaternary (Table 7). Hoover and others (1981) suggest 25 to 100 m of erosion of stratigraphic unit QTa (0.9 to 1.1 my old) above the present surface. These data give an erosion rate of about 10 cm/1000 yr. The U.S. Geological Survey lists 2.2 to 8.2 cm/1000 yr. as the maximum rates of stream incision in Tertiary and Quaternary surfaces in the yucca Mountain area (Table 8), and less than 10 cm/1000 yr. during the last 300,000 years on Forty Mile Wash. The Department of Energy (1984) presents a mean, maximum stream incision rate of 5 cm/1000 yr. and suggests that the rate has been less than 10 cm/1000 yr. for the last 300,000 years.

As with the paleoclimate data, the compatibility of the various types of data and rates is highly variable. Data for the NTS area are greatly limited and inadequate to support the overall conclusions as presented in the Department of Energy (1984) Draft Environmental Assessment.

EROSION AT THE NEVADA TEST SITE

How does all this relate to the NTS? Two of the works previously cited are worth quoting here. The quotes reflect 1) the incompleteness of data on the total degradation at the NTS and 2) the need for a complete, highly detailed geomorphic study to adequately assess he erosion potential of the NTS.

1) "Stream incision rates are only one measure of the total Quaternary erosion that has occurred in the Site Vicinity. no data are yet available for rates of hillslope erosion, deflation by wind, or sediment yield. These are the principal measurements necessary to characterize total Quaternary degradation at the Site." (U.S. Geological Survey, 1984, p. 16), and

Table 7 Approximate rates of relative vertical tectonic adjustment or burial at selected locations in the southwestern Great Basin during the late Neogene and Quaternary.

Location	Rate, m/1000 yr (mm/yr)	Comment
S. Amargosa Desert valley[1]	<0.01[2]	Based on an ash bed in lake deposits about 5 m below the surface; "Ewing" clay pit, just north of Ash Meadows
Crater Flat, central	<0.01[2]	Basalt dated by K-Ar at 1.2 m.y. (Crowe and others, 1983) is at the present surface and has not been deformed or subsided into the basin
Crater Flat, eastern	<0.01[2]	Based on an offset in alluvium at trench 1 (allowing for 0.6 m of erosion) of 3.0 m in 1.1 m.y.[3] Swadley and Hoover, 1983
Crater Flat southeastern	<0.02	Offset of alluvium in trench 3 in a minimum time of 40,000 Actual time was probably closer to 260,000 yr (Swadley and Hoover, 1983)
Crater Flat, USW VH-2 drill hole	0.03	Burial of basalt about 11 m.y. old (R. F. Marvin. U.S. Geol. Survey, written commun., 1983)

[1]Relative rate of subsidence or burial is based on an ash bed that occurs at these three locations, and is believed to correlate (Izett, 1981; Sarna-Wojcicki and others, 1980; R. L. Hay, written commun., 1979); the ash is dated at about 3 m.y. by paleomagnetic, stratigraphic, K-Ar and fission-track techniques (Liddicoat and Smith, 1979).

[2]Maximum rate; figures using additional decimal places are considered to imply unrealistic accuracy.

[3]The age of 1.1 m.y. assumes that basalt ash in the fault in this trench came from one of four centers in Crater Flat of this age (Crowe and others, 1983). Logic supports this conclusion (Swadley and others, U.S. Geological Survey, written commun., 1984), but does not rule out the possibility that the ash came from the 0.3 m.y.-old Big Dune Center. If the latter is the case, the rate becomes 0.01 m per 1,000 yr.

Location	Rate, m/1000 yr (mm/yr)	Comment
Yucca Mountain	0.03	Based on maximum of 460 m of Tiva Canyon Member in last 12.8 m.y. For the Quaternary, a very conservative estimate is <0.01 m/1000 yr., based on maximum credible amount of displacement (10 m) in Quaternary time (see text).
N.W. Frenchman Flat[1]	0.06	Burial of ash bed at depth of drill hole UE5n; not in most active part of the Frenchman Flat basin
S. Yucca Flat	0.16	Based amount of displacement of a basalt in drill holes UE1h and UE6d (fig. 11); basalt is (R.F. Marvin, U.S. Geol. Survey, written commun., 1980).
Searles Valley[1]	0.22	Burial of ash bed in core at depth of 691 m
Death Valley-foot of of Black Mountains	0.3	Based on displacement of Artist's Drive Formation, which is 6-8 m.y. old according to Fleck (1970a). Estimated here to be about 1,525 m (5,000 ft) in 5 m.y.
Sierra Nevada-Owens Valley-White-Inyo Mountains	0.4	Average of 9 estimates (range 0.2-1.0 m/1000 yr) from various sources[2]. Quaternary rate is probably higher.
Coso Range - Rose Valley	1.8	Offset of 2.5 m.y. – old lava flow (Roquemore, 1980; Healy and Press, 1964).

[1]Relative rate of subsidence or burial is based on an ash bed that occurs at these three locations, and is believed to correlate (Izett, 1981; Sarna-Wojcicki and others, 1980; R. L. Hay, written commun., 1979); the ash is dated at about 3 m.y. by paleomagnetic, stratigraphic, K-Ar and fission-track techniques (Liddicoat and Smith, 1979).

[2]Owens Valley—Bachman (1978); central Sierra Nevada—Curry (1971), and Huber (written commun., 1980); Mono Lake basin—Gilber and others (1968).

Table 8 Maximum depth and rates of stream incision in Tertiary and Quaternary surfaces in the Yucca Mountain area.

Surface[a] of Unit	Approx. Age (Years)	Maximum Depth (m)	Maximum Rate[b] ($m/10^3$ Years)	Location
Q2b	1.6×10^5 [c]	8.5	0.053	Fortymile Wash
Q2c	3×10^5 [d]	25.9	0.082	Fortymile Wash
Tpc	10×10^6 [e]	218.2	0.022	Western Yucca Mountain

(from U.S. Geological Survey, 1984)

[a] For meaning of unit designations, see Hoover and others, (1981).
[b] Corrections for differences in slope, topographic relief, or drainage basin area have not been made in calculating the maximum rates of stream incision. All such corrections would tend to decrease the rates.
[c] Q2b age is maximum determined by U-Th disequilibrium method.
[d] Q2c age is average of two U-Th disequilibrium ages.
[e] Tpc (Tiva Canyon Member of the Paintbrush Tuff) uplift age is determined from two minimum K-Ar ages for the Rainier Mesa Member, which overlies the traces of faults along which blocks of the Tiva Canyon Member were uplifted.

2) "If the required geomorphic, climatic, tectonic and hyydrologic data are no available at a perspective site, as is usually the case, geomorphic stability must then be determined by a complete geomorphic evaluation of the site based on the most conservative assumptions." (Schumm and Chorley, 1983, p. 111).

To adequately address the potential erosion at the proposed Yucca Mountain site, data pertinent to all the aspects of climate and erosion, as presented in the previous sections of this report, are necessary. Estimates of the climatic reconstruction variables, mean annual temperature, and mean annual precipitation, have been presented. The current average annual precipitation ranges from 6 cm at the lowest elevations to about 50 cm at the highest elevations with an average between 10 to 25 cm (Squires and young, 1984). However, theories presented to explain the paleoclimate data are varied. Therefore, the most conservative approach must be taken. In this case, analyses should at least be based on pluvial climate interpretations that call for the maximum amount of increased precipitation, or 100% over present conditions (Table 1).

Likewise, estimates of potential erosion need to be conservative. The Department of Energy (1984) has formally presented an erosion rate for the NTS of less than 10 cm/1000 yr. or 1 meter/10,000 yr., primarily based on the work of Hoover and others (1981). These data are quite in agreement with the published literature discussed earlier in this report. However, as was previously noted by this author during review of the Department of Energy (1984) Draft Environmental assessment, and in a letter to ben Rice (NRC), dated March 5, 1985, these rates are derived from three data points (Table 8). In no way can realistic comments regarding favorable and adverse conditions and qualifying and disqualifying conditions be based on these data. Considerable additional data will be necessary to form even a preliminary understanding of the erosion potential at the NTS.

Further investigations of valley incision, hillslope erosion, and escarpment retreat are necessary. These data should then be combined with uplift/subsidence data and sediment yield data to give a complete picture of the potential future erosion at the NTS. Investigations of stream incision on Fortymile Wash and probably yucca Wash are important to understanding the past erosional history of these major drainages. Most likely the U.S. Geological Survey (1984) is correct in assuming some of the increase in channel incision along Fortymile Wash was initiated when it captured Beatty Wash. However, additional data on stream deposits (terraces), stream and terrace profiles, and associated radiometric dates of these varied deposits are necessary to tie the fluvial chronology with the already established alluvial chronology surrounding the major washes. These data will also add greatly to the reconstruction of the Quaternary geomorphic development of the site area, such as the capture of Beatty Wash.

Estimates of hillslope erosion are necessary, especially as they relate to the eastern slopes of Yucca Mountain and the Drill Hole Wash area. Hillslope erosion studies should be conducted along all the watersheds (drainage basins) on the eastern side of Yucca Mountain. The most likely method is the USLE (previously discussed). The hillslope erosion studies should be certain to include studies of the various lithologic units present, ranging from alluvium to the densest of the volcanic formations. Comparison and contrast of these data should help in understanding sheet wash and rill erosion, the Quaternary geomorphic development of the area, and depicting anomalous areas suggestive of possible uplift or subsidence. Attempts to apply the USLE and to adequately choose the appropriate variables to the equation are necessary. Presently, with no available data on hillslope erosion, use of data presented on Table 5 would result in estimates ranging from 2 to 8.2 mm/yr. which converts to 20 to 82 m/10,000 yr. are possible.

Estimates of escarpment retreat on the west face of Yucca Mountain are necessary to completely address the erosion hazards at the NTS. The complex slope formed by the various exposed lithologic units needs to be evaluated in leu of the maximum postulated climatic change. With no data presented regarding escarpment retreat along the west face of Yucca Mountain, estimates based on Table 6 could range a high as 2 to 6 m/10,000 yr. Although these rates are based on sandstone in a semiarid/arid environment, they have to be considered to be in the general range of potential escarpment retreat for Yucca Mountain.

The theoretical examples from tabulated data on hillslope erosion and escarpment retreat are considered intuitively excessive, but are used to demonstrate the need for detailed, site specific evaluations. Generation of these detailed erosion data, combined with uplift/subsidence rates and sediment yield data should adequately depict the potential erosion hazard at the NTS.

SUMMARY

In summary, paleoclimate reconstruction applicable to the NTS area are numerous and varied, and so are their results. Because of these discrepancies, only the most conservative estimates of pluvial conditions should be applied for future predictions of a paleoclimate and erosion potential, i.e. decrease temperature 10° to 11° C and increase present precipitation 100%. The estimated erosion rates presented for the Yucca Mountain Site are in quite good agreement with published rates in the literature. However, the data base for these rates is inadequate and numerous additional studies, especially valley incision, hillslope erosion and escarpment retreat, need to be completed. By applying theoretical, tabulated data to the Yucca Mountain Site, unfavorable rates can be estimated. Although the intuitive suggests erosion should not be a critical problem at the Yucca Mountain Site, further data need to be generated to confirm these intuitions.

REFERENCE CITED

1. Antevs, E. V., 1952, Cenozoic climates of the Great Basin; Geologisches Rundschau, v. 40, p. 94-108.

2. Brackenridge, G. R., 1978, Evidence for a cold,dry full-glacial climate in the American southwest; Quaternary Research, v. 9, p. 22-40.

3. Bradley, R. S., 1985, Quaternary Paleoclimatology; Methods of paleoclimatic reconstruction; Winchester, Massachusetts, 472p.

4. Carr, W. J., 1984, Regional structural setting of Yucca Mountain, southwestern Nevada, and late Cenozoic rates of tectonic activity in part of the southwestern Great Basin, Nevada and California; U. S. Geological Survey Open-File Report 84-854, 109p.

5. Cole, Kenneth L., and Webb, Robert H., 1985, Late Holocene vegetation changes in Greenwater Valley, Mojave Desert, California; Quaternary Research, v. 23, p. 227-235.

6. Damon, P. E. Shafaqullah, M., and Scarborough, R. B., 1978, Revised chronology for critical stages in evolution fo the lower Colorado River; Geological Society of America, Abstracts with Programs, v. 10, p. 101-102.

7. Dohrenwend, John C., Wells, Stephen G., Turrin, Brent, D., and McFadden, Leslie D., 1984, Rates and trends of late Cenozoic landscape degradation in the area of the

Cima volcanic field, Mojave Desert, California; Geological Society of America, 1984 Annual Meeting field trip guidebook 14, Reno, Nevada, p. 101-115.

8. Dohrenwend, John C., Turrin, Brent D., and Diggles, Michael F., 1985, Topographic distribution of dated basaltic lava flows in the Reveille Range, Nye County, Nevada: Implications for late Cenozoic erosion of upland areas in the Great Basin; Geological Society of America Abstracts with Programs, 1985, Cordilleran Section, v. 17, No. 6, p. 352.

9. Gable, Dolores, and Hatton, Tom, 1980, Vertical crustal movements in the conterminous United States over the past 10 million years; U. S. Geological Survey Open-File Report 80-180, 9p.

10. Galloway, R. W., 1970, The full-glacial climate in the southwestern United States; annals of the Association of American Geographers, v. 60, p. 245-256.

11. Galloway, R. W., 1983, Full-glacial southwestern United States; Mild and wet or cold and dry?; Quaternary Research, v. 19, p. 236-248.

12. Hamblin, W. K., Damon, P. E., and Bull, W. B., 1981, Estimates of vertical crustal strain rates along the western margins of the Colorado Plateau; Geology, v. 9, p. 293-298.

13. Hoover, D. L., Swadley, W. C., and Gordon, A. J., 1981; Correlation characteristics of surficial deposits with a description of surficial stratigraphy in the Nevada Test Site region; U. S. Geological Survey Open-File Report 81-512, 27p.

14. LaMarche, V. C., Jr., 1973, Holocene climatic variations inferred from treeline fluctuations in the White Mountains, California; Quaternary Research, p. 632-660.

15. Leopold, L. B., 1951, Pleistocene climate in New Mexico; American Journal of Science, v. 249, p. 152-168.

16. Mifflin, M. D., and Wheat, M. M., 1979, Pluvial lakes and estimated pluvial climates of Nevada; Nevada Bureau of Mines and Geology Bull. 94, 57p.

17. Morrison, R. B., 1964, Soil stratigraphy; principals, applications to differentiation and correlation of Quaternary deposits and landforms,a nd applications to soil science; University of Nevada, Ph.D. dissertation, Reno, Nevada, 178p.

18. Schumm, S. A., and Chorley, R. J., 1983, Geomorphic controls on the management of nuclear waste; U. S. Nuclear Regulatory Commission Report no. NUREG/CR-3276, 137p.

19. Smith, George, I., 1984, Paleohydrologic regimes in the southwestern Great Basin, 0-3.2 my ago, compared with other long records of "global" climate; Quaternary Research v. 22, p. 1-17.

20. Spaulding, W. Geoffrey, 1983, Vegetation and climates of the last 45,000 years in the vicinity of the Nevada Test Site, south-central Nevada; U.S. Geological Survey Open-File Report 83-535, 205p.

21. Spaulding, W. Geoffrey, Robinson, Stephen W., and Paillet, Frederick L., 1984, Preliminary assessment of climatic change during late Wisconsin time, southern Great Basin and vicinity, Arizona, California, and Nevada; U. S. Geological Survey Water-Resources Investigations Report 84-4328, 40p.

22. Squires, Robert R., and Young, Richard L., 1984, Flood potential of Fortymile Wash and its principal southwestern tributaries, Nevada Test Site, southern Nevada; U. S. Geological Survey Water-Resources Investigations Report 83-4001, 33p.

23. U. S. Department of Agriculture, 1977, Preliminary guidance for estimating erosion on areas disturbed by surface mining activities in the interior western United States. U. S. Environmental Protection Agency Interim Final Report No. EPA-908/4-77-005, 26p.

24. U. S. Department of Energy, 1984, Draft Environmental Assessment, Yucca Mountain Site, Nevada research and development area, Nevada; U. S. Department of Energy, Washington D. C., 816p.

25. U. S. Geological Survey, 1984, A summary of geological studies through January 1, 1983, of a potential high-level radioactive waste repository site at Yucca Mountain,

southern Nye County, Nevada; U. S. Geological Survey Open-File Report 84-792, (Geomorphology Section), p. 7-16.

26. Van Devender, T. R., 1973, Late Pleistocene plants and animals of the Sonoran Desert, a survey of ancient packrat middens in southwestern Arizona; Tucson, Arizona, University of Arizona, Ph.D. dissertation, 179p.

27. Wells, S. G., McFadden, L. D., Dohrenwend, J. C., Bullard, T. F., Feilberg, B. F., Ford, R. L., Grimm, J. P., Miller, J. R., Orbock, S. M., and Pickle, J. D., 1984, Late Quaternary geomorphic history of the Silver Lake area, eastern Mojave Desert, California; An example of the influence of climatic change on desert piedmonts; Geological Society of America 1984 Annual Meeting field trip guidebook 14, Reno, Nevada, p. 69-87.

28. Winograd, I. J., 1974, Radioactive waste storage in the arid zone; EOS Transactions, American Geophysical Union, v. 55, no. 10, p. 884-894.

29. Winograd, Issac J., and Doty, Gene C., 1980, Paleohydrology of the southern Great Basin, with special reference to water table fluctuations beneath the Nevada Test site during the late (?) Pleistocene; U. S. Geological Survey Open-File Report 80-569, 91p.

30. Young, Anthony, 1972, Slopes; Oliver and Boyd, Edinburgh, 288p.

REFERENCES REVIEWED BUT NOT CITED

1. Bishop, Paul, 1985, Southeast Australian late Mesozoic and Cenozoic denudation rates; A test for late Tertiary increases in continental denudation; Geology, v. 13, p. 479-482.

2. Donnelly, Thomas W., 1982, Worldwide continental denudation and climatic deterioration during the late Tertiary; Evidence from deep-sea sediments; Geology, v. 10, no. 9, p. 451-454.

3. Etkins, Robert, and Epstein, Edward S., 1982, The rise of global mean seal level as and indication of climate change; Science, v. 215, p. 278-288.

4. Flint, Richard Foster, 1971, Glacial and Quaternary Geology; New York, John Wiley and Sons, Inc., 892p.

5. Mayer, Larry, 1984, Dating Quaternary fault scarps formed in alluvium using morphologic parameters; Quaternary Research, v. 22, p. 300-313.

6. Nash, David B., 1984, Morphologic dating of fluvial terrace scarps and fault scarps near west Yellowstone, Montana; Geological Society of America Bull., v. 95, p. 1413-1424.

7. Scott, Robert B., Bath, Gordon D., Flanigan, Vincent J., Hoover, Donald B., Rosenbaum, Joseph G., and Spengler, Richard W., 1984, Geological and geophysical evidence of structures in northwest-trending washes, Yucca Mountain, southern Nevada, and their possible significance to a nuclear waste repository in the unsaturated zone; U. S. Geological Survey Open-File Report 84-567, 23 p.

8. Swadley, W. C., and Hoover, D. L., 1983, Geology of faults exposed in trenches in Crater Flat, Nye County, Nevada; U. S. Geological Survey Open-File Report 83-608, 15p.

9. Swadley, W. C., Hoover, D. L., and Rosholt, J. N., 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, 42p.

10. Szabo, B. J., and Kyser, T. K., 1985, Uranium, Thorium isotope analyses and Uranium-series ages of calcite and and opal, and stable isotopic compositions of calcite from drill cores UE25a #1, USW G-2, and USW G-3/GU-3, Yucca Mountain, Nevada, U. S. Geological Survey Open-File Report 85-224, 25p.

11. Szabo, B. J., and O'Malley, P. A., 1985, Uranium-series dating of secondary carbonate and silica precipitates relating to fault movements in the Nevada Test Site region and of caliche and travertine samples from the Armagosa Desert; U. S. Geological Survey Open-File Report 85-47, 12p.

12. Szabo, B. J., Carr, W. J., and Gottschall, W. C., 1981, Uranium-Thorium dating of Quaternary carbonate accumulations in the Nevada Test Site region, southern Nevada; U. S. Geological Survey Open-File Report 81-119, 35p.

ADDITIONAL READING

1. Adam, D. P., and West, G. J., 1983, Temperature and precipitation estimates through the last glacial cycle from Clear Lake, California, pollen data; Science, v. 219, p. 168-170.

2. Antevs, E., 1948, Climatic changes and pre-white man; University of Utah Bull, v. 36, 168-191.

3. Beatley, J. C., 1975, Climates and vegetation pattern across the Mojave/Great Basin desert transition of southern Nevada; American Midland Naturalist, v. 93, p. 53-70.

4. Begin, Z. B., 1979, Aspect of degradation of alluvial streams in response to base-level lowering; Unpublished Ph.D. dissertation, Colorado State University, Fort Collins, Colorado, 239p.

5. Begin, Z. B., Meyer, D. F., and Schumm, S. A., 1980, Knickpoint migration due to base level lowering; Journal Waterway, Port, Coastal and Ocean Div., American Society of Civil Engineers Proceedings, v. 106, p. 369-388.

6. Bell, F. C., 1979, Precipitation; in Goodall, D. W., and Perry, R. A., eds., Arid-land ecosystems-structure, function, and management, New York, Cambridge University Press, p. 373-392.

7. Berger, A., 1980, The Milankovitch astronomical theory of paleoclimates; A modern review; Vistas Astronomy, v. 24, p. 103-122.

8. Billings, W. D., 1949, The shadscale vegetation zone of Nevada and eastern California in relation to climate and soils; American Midland Naturalist, v. 42, p. 87-109.

9. Born, S. M., and Ritter, D. F., 1970, Modern terrace development near Pyramid Lake, Nevada, and its geologic implications; Geological Society of American Bull.; v. 81, p. 1233-1242.

10. Bradley, R. S., 1976, Seasonal precipitation fluctuations in the western United States during the late nineteenth century; Monthly Weather Reviews, v. 104, p. 501-512.

11. CLIMAP Project Members, 1976, The surface of the ice-age earth; Science, v. 191, p. 1131-1137.

12. Cooke, R. V., and Warren, A., 1973, Geomorphology in deserts; University of California Press, Los Angeles.

13. Curry, R. R., 1969, Holocene climatic and glacial history of the Sierra Nevada, California; Geological Society of American Special Paper no. 123, p. 1-47.

14. Denton, G. H., and Karlen W., Holocene climatic variations - their pattern an possible cause; Quaternary Research, v. 3, p. 155-205.

15. Douglass, A. E., 1914, A method of estimating rainfall by the growth of tress; in The Climatic Factor, Huntingdon, E., ed., Carnegie Institution of Washington Publication No. 1982, Washington D. C., p. 101-122.

16. Emiliani, C., 1955, Pleistocene temperatures; Journal of Geology, v. 63, p. 538-578.

17. Flint, R.F., 1976, Physical evidence of Quaternary climatic change; Quaternary Research, v. 6, p. 519-528.

18. Frakes, L. A., 1979, Climates through geologic time; Amsterdam, Elsevier.

19. Fritts, H. C., 1965, Tree-ring evidence for climatic changes in western North America; Monthly Weather Review, v. 93, p. 421-443.

20. Gates, W. L., 1976, Modeling the ice-age climate; Science, v. 191, p. 1138-1144.

21. Gregory, K. J., 1976, Drainage networks and climate; in Derbyshire, E., ed., Geomorphology and Climate, John Wiley and Sons, London, p. 289-315.

22. Grove, J. M., 1979, The glacial history of the Holocene; Progress in Physical Geography, v. 3, p. 1-54.

23. Hare, K. L., Late Pleistocene and Holocene climates – some persistent problems; Quaternary Research, v. 6, p. 507-518.

24. Harmon, R. S., Thompson, P., Schwarcz, H. P., and Ford, D. C., 1978, Late Pleistocene paleoclimates of North America as inferred from stable isotope studies of Speleothems; Quaternary Research, v. 9, p. 54-70.

25. Houghton, J. G., Sakamoto, C. M., and Gifford, R. O., 1975, Nevada's weather and climate; Nevada Bureau of Mines Special Publication 2, 78p.

26. Huning, J. R., 1978, A characterization of the climate of the California desert; Riverside, Desert Planning Staff, California Bureau of Land Management unpublished report, 200p.

27. Imbrie, John, and Imbrie, J. Z., 1980, Modeling the climatic response to orbital variations; Science, v. 207, p. 943-953.

28. Jensen, J. M. L., and Painter, R. B., 1974, Predicting sediment yield from climate and topography; Journal of Hydrology, v. 21, p. 371-380.

29. Klein, J., Lerman, J. C., Damon, P. E., and Ralph, E. K., 1982, Calibration of radiocarbon dates; Tables based on the consensus data of the workshop on calibrating the radiocarbon time scale; Radiocarbon, v. 24, p. 103-150.

30. Knox, J. C., 1979, Hydrogeomorphic implications of climatic change; U. S. Army Coastal Engineering Research Center Report DACW 72-78-C-0035, Fort Belvoir, Virginia, 132 p.

31. Kutzbach, J. E., 1975, Diagnostic studies of past climate; in the physical basis of climate and climate modelling; GARP Publication no. 16, Geneva, World Meteorological Organization, p. 119-125.

32. Kutzbach, J. E., 1976, The nature of climate and climatic variations; Quaternary Research, v. 6, p. 471-480.

33. Kutzbach, J. E. , 1981, Monsoon climate of the early Holocene-climate experiment with the Earth's orbital parameters for 9,000 years ago; Science, v. 214, p. 59-61.

34. LaMarche, V. C., Jr., and Fritts, H. C., 1971, Anomaly patterns of climate over the western United States, 1700-1930, derived from principal component analysis of tree ring data; Monthly Weather Review, v. 99, p. 138-142.

35. LaMarche, V. C., and Stockton, C. W., 1974, Chronologies from temperature-sensitive Bristlecone Pines at upper treeline in western United States; Tree Ring Bull.; v. 34, p. 21-45.

36. Lamb, H. H., 1977, Climate present, past and future; Methuen and Company, London, v. 2, 835p.

37. Mehringer, P. J., Jr., 1965, Late Pleistocene vegetation in the Mojave Desert of southern Nevada; Journal of the Arizona Academy of Science, v. 3, p. 172-188.

38. Mehringer, P. J., Jr., 1977, Great Basin Later Quaternary environments and chronology; in Models and Great Basin Prehistory, a Symposium, Fowler, D. D., ed., Desert Research Institute Publication 12, p. 113-167.

39. Mehringer, P. J., Jr., and Warren, C. N., 1976, Marsh, dune, and archaeological chronology, Ash Meadows, Armagosa Desert, Nevada in Elston, R., ed., Holocene environmental change in the Great Basin, Nevada Archaeological Survey Research Paper 6, p. 120-150.

40. Mitchell, J. M., 1976, An overview of climate variability and its causative mechanism; Quaternary Research, v. 6, p. 481-494.

41. Mitchell, V. L., 1976, The regionalization of climate in the western United States; Journal of Applied Meteorology, v. 15, p. 920-927.

42. Morrison, R. B., 1965, Quaternary geology of the Great Basin, in The Quaternary of the United States, Wright, H. E., and Frey, D. G., eds., Princeton, New Jersey, Princeton University Press, p. 265-286.

43. National Defense University, 1978, Climate change to the year 2000-A survey of expert opinion; Research Directorate, Fort Lesley J. McNair, Washington, D. C., 109p.

44. Neftel, A, Oeschger, H., Schwander, J., Stauffer, B., and Zumbrunn, R., 1982, Ice core sample measurements give atmosphere CO_2 content during the past 40,000 years; London, Nature, v. 295, p. 220-223.

45. Pisias, N. G., and Moore, T. C., 1981, The evolution of Pleistocene climate; a time series approach; Earth Planetary Science Letters, v. 52, p. 450-458.

46. Pollard, D., 1982, A simple ice sheet model yields realistic 100,000 year glacial cycles; London, Nature, v. 296, p. 334-338.

47. Porter, S. C., 1971, Fluctuations of late Pleistocene alpine glaciers in western North America; in Turekian, K. K., ed., The late Cenozoic glacial ages; New Haven, Yale University Press, p. 307-330.

48. Porter, S. C., 1981, Glaciological evidence of Holocene climatic change; in Climate and History, Wigley, T. M. L., Ingram, M. J., and Farmer, G., eds., Cambridge, Cambridge University Press, p. 82-110.

49. Rice, R. J., 1980, Rates of erosion in the Little Colorado Valley, Arizona; in Cullingford, R. A., Davidson, D. A., and Lewin, J., eds., Timescales in geomorphology, Wiley Interscience, New York, p. 317-331.

50. Schumm, S. A., 1963, Disparity between modern rates of degradation and orogeny; U. S. Geological Survey Professional Paper 454-H, 13p.

51. Schuum, S. A., and Hadley, R. F., 1961, Progress in the application of landform analysis in studies of semiarid erosion; U. S. Geological Survey Circular 437, 14p.

52. Schumm, S. A., Harvey, M. D., and Watson, C. C., 1983, Incised channels: morphology, dynamics and control; Water Resources Publications Monograph, in press.

53. Shackleton, N. J., and Opdyke, N. D., 1973, Oxygen isotope and paleomagnetic stratigraphy of Pacific core v28-239: oxygen isotope temperatures and ice volumes on a 10^5 year and 10^6 year scale; Quaternary Research, v. 3, p. 39-55.

54. Snyder, C. T., and Langbein, W. B., 1962, The Pleistocene lake in Spring Valley, Nevada, and its climatic implications; Journal of Geophysical Research, v. 67, p. 2385-2394.

55. Stoddart, D. R., 1969, Climatic geomorphology; Review and Assessment; Progress in Geography, London, v. 1, p. 160-222.

56. Thompson, R. S., and Mead, J. I., 1982, Late Quaternary environments and biogeography in the Great Basin; Quaternary Research, v. 17, p. 39-55.

57. Trimble, S. W., 1977, The fallacy of stream equilibrium in contemporary denudation studies; American Journal of Science, v. 277, p. 876-887.

58. Van Devender, T. R., 1977, Holocene woodlands in the southwestern deserts; Science, v. 198, p. 189-192.

59. Van Devender, T. R., and Spaulding, W. G., 1979, Development of vegetation and climate in the southwestern United States; Science, v. 204, p. 701-710.

60. Webb, T., and Bryson, R. A., 1972, Late and post-glacial climatic change in the northern mid-west USA; quantitative estimates derived from fossil pollen spectra by multivariate statistical analysis; Quaternary Research, v. 2, p. 70-115.

61. Wells, P. V., 1976, Macrofossil analysis of woodrat (Neotoma) middens as a key to the Quaternary vegetational history of arid America; Quaternary Research, v. 6, p. 223-248.

62. Wells, P. V., 1979, An equable glacioluvial in the West-Pleniglacial evidence of increased precipitation on a gradient from the Great Basin to the Sonoran and Chichuahuan deserts; Quaternary Research, v. 12, p. 311-325.

63. Wells, P. V., and Jorgensen, C. D., 1964, Pleistocene wood rate middens and climatic change in Mojave Desert - A record of juniper woodlands; Science, v. 143, p. 1171-1174.

64. Williams, L. D., and Wigley, T. M. L., 1983, A comparison of evidence for late Holocene summer temperature variations in the northern hemisphere; Quaternary Research, v. 20, p. 286-307.

65. Wintle, A. G., 1978, A thermoluminescence dating study of some Quaternary calcite; potential an problems; Canadian Journal of Earth Science, v. 15, 1977-1986.

66. Wintle, A. G., and Huntley, D. J., 1982, Thermoluminescence dating of sediments; Quaternary science Reviews, v. 1., p. 31-54.

67. Wollin, G., Ryan, W. B., and Ericson, D. B., 1977, Paleoclimate, paleomagnetism and the eccentricity of the Earth's orbit; Geophysical Research Letters, v. 4, 267-270.

68. Wollin, G., Ryan, W. B., and Ericson, D. B., 1978, Climatic changes, magnetic intensity variations and fluctuations of the eccentricity of the Earth's orbit during the past 2,000,000 years and a mechanism which may be responsible for the relationship; Earth Planetary Science Letters, v. 41, p. 395-407.

69. Wolman, M. G., and Gerson, R., 1978, Relative scales of time and effectiveness of climate in watershed geomorphology; Earth Surface Precesses, v. 3, 189-208.

70. Wright, H. E., Jr., 1972, Interglacial and postglacial climates – the pollen record; Quaternary Research, v. 2, p. 274-282.