STATE-OF-THE-ART FOR EVALUATING
THE POTENTIAL EFFECTS OF EROSION
AND DEPOSITION ON A RADIOACTIVE
WASTE REPOSITORY

MASTER

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1. INTRODUCTION

This report is one of a series of reports prepared for the Lawrence Livermore Laboratory under Purchase Order 5696709 to review the state-of-the-art for evaluating the potential impact of future geologic processes on the integrity of a deep, high-level radioactive-waste repository. The following study identifies the potential consequences of surface erosion and deposition on subsurface repository containment characteristics and assesses the ability to measure and predict quantitatively the rates and corresponding extent of these processes in the long term.

Numerous studies of the magnitudes and rates of surficial erosion and deposition that have been used to determine the minimum allowable depth for a geologic repository (300 m - NRC Code of Federal Regulations, Part 60.122, Draft 10) are cited in this report. Measurement and interpretation of potential rates and extent of surficial processes in these studies involved considerable uncertainty, and the implications of this uncertainty on presently proposed repository siting criteria are addressed herein. Important concepts that should be considered when developing siting criteria to protect against deleterious effects arising from future erosion or deposition are highlighted.

Erosion agents that could affect deep repositories are distinguished in this report so that their individual and combined impacts may be examined. This approach is recommended when evaluating potential repository sites in diverse environments that are susceptible to different agents of erosion. In contrast, agents of sedimentation are not differentiated in this report because of their relatively minor impact on a deep repository.

2. EXECUTIVE SUMMARY

This report reviews the state-of-the-art for evaluating the potential impact of surficial erosion and deposition on a deep radioactive waste repository.

Several detrimental impacts by erosion are identified:

- Erosion may exhume the repository and permit direct contact of the concentrated radioactive wastes with the accessible environment.
- Erosion may shorten potential paths of waste migration from the repository to the accessible environment via groundwater seepage or penetrate impermeable barriers retarding such seepage.
- Erosion may penetrate the buffer zone of rock surrounding a repository required to dissipate thermal energy released by waste decay and subsurface stresses produced during repository construction.

Surficial deposition over a repository is shown generally to improve waste containment capabilities by increasing the depth of burial. Only in special cases will rapid deposition influence repository stability by producing nonuniform subsurface stresses.

Fluvial, glacial, fluvio-glacial and eolian processes of erosion are examined to define unique characteristics of each process that may potentially harm a deep repository. Both channel and regional erosion by fluvial processes are unpredictable and depend on climate, relief, elevation, vegetation, and the mechanical and chemical resistance of surface materials. Because fluvial erosion is a nonsteady-state process, future rates of erosion cannot be predicted accurately, and it is beyond the state-of-the-art to predict the depth of fluvial erosion at a given location after a given length of time. However, the ultimate depth of fluvial erosion is limited by the erosion base level, which may be sea level in coastal areas or at higher elevations in interior regions, depending on lithology, topography and characteristics of local drainage systems.

Rates of glacial scouring and eolian erosion are not predictable, and the potential depth of erosion in loose, erodible lithologies by these processes is not limited. However, eolian erosion is limited by bedrock, and eolian processes have been known to scour bedrock surfaces to a depth of only a few centimeters. The depth of glacial scouring into bedrock depends on

the characteristics of the glacier and the type of bedrock. Glacial scouring has extended to depths exceeding 600 m in weak, fractured sedimentary rock and to depths less than 40 m in hard, crystalline rock.

The extent of fluvioglacial erosion is somewhat limited by sea level, but scouring during catastrophic outbursts of glacial lakes has incised bedrock to depths up to 120 m. It is possible that scouring could extend below sea level. The locations of many extinct fluvioglacial channels can be identified morphologically, but many channels have been obscured by glacial sediments and it is possible that the frequency of fluvioglacial erosion channels is greater than is presently recognized. The location of future channels cannot be predicted, and this process of erosion may pose a serious hazard to repositories located in regions previously covered by glaciers or subjected to drainage by glacier meltwater.

Rates of modern erosion and the extent of past erosion have been determined by measuring sediment load concentrations in streams, measuring surface erosion of natural or artificially placed materials at discrete locations by precise leveling, and examination of landform and stratigraphic changes that occurred during a geologically interpreted span of time. The latter method is useful for determining the maximum extent of erosion of catastrophic processes that may have been active at a repository site during the past, and the former methods can be used to compare the susceptibility of modern landscapes to erosion. Measurements of regional and local rates and extents of erosion in a wide variety of environments are reported herein, but the conceptual and technical uncertainties involved in these measurements must be considered before they are used to evaluate the potential impact of erosion on a buried repository.

The following recommendations are made to assist in siting deep geologic repositories to minimize the impact of surface erosion:

- Repositories should not be sited in regions where the rate of tectonic uplift exceeds the rate of regional denudation, because these regions will probably experience increasing rates of erosion in the future.
- Because of potential future climate fluctuations that may change the elevation of sea level, repositories in tectonically stable regions should be buried at least 130 m beneath the erosion base level elevation to prevent exhumation by fluvial erosion.

- Statistically significant rates of regional erosion measured for a proposed repository site should be examined to identify the relative susceptibility of the region to erosion by surficial processes. These rates also should be examined to determine the relative permanency of local base levels or erosion that may prevail at potential repository sites.
- Geologic studies of morphology and subsurface stratigraphy should be conducted at each potential repository site to determine the existing stage of landscape evolution and the maximum depth of bedrock erosion by processes active during the Quaternary period (e.g., glaciation). Repositories should not be sited in areas exhibiting the youthful stage of landscape evolution, and repositories should be buried at sufficient depth to prevent exhumation by recurrence of catastrophic erosion processes in the future.
- Repositories should not only be buried at sufficient depth to prevent future exhumation, but also to prevent penetration of impermeable barriers retarding waste migration, penetration of the required buffer zone of rock surrounding a repository, and unacceptable shortening of waste migration paths from the repository to the accessible environment.

3. IMPACT OF EROSION AND DEPOSITION ON A DEEP RADIOACTIVE WASTE REPOSITORY

3.1 Introduction

The development of qualification criteria for deep geologic repository sites has emphasized the need to maintain isolation from surface geologic processes. The following criterion has been proposed by the Office of Nuclear Waste Isolation (ONWI-33 (2) Draft, January, 1980):

"Section 2.1.1 The minimum depth of the repository horizon shall be such that credible natural processes acting at the surface will not unacceptably affect repository performance.

In order to establish this depth, erosion and denudation rates, and other phenomena, must be evaluated to show that they would not unacceptably affect repository performance."

The following discussion clarifies how surface erosion and sedimentation may adversely affect repository performance and identifies important phenomena related to these processes that should be evaluated.

3.2 Exhumation

Probably the most severe impact surficial geologic processes could have on a high-level radioactive-waste repository would be uncovering the repository and permitting direct contact of the concentrated radioactive wastes with the biosphere. Consequently, many studies of erosion processes have been directed toward establishing the repository depth required to prevent exhuming of wastes in the long term (e.g., Gera and Jacobs, 1972 and Ekren, et al., 1974).

Minimum allowable repository depths are usually obtained by multiplying interpreted average rates of denudation in the repository area (given in terms of depth per unit time) by the time considered necessary to assure safe containment of the radioactive waste. This containment period has been estimated to vary from 1,000 years (referring specifically to containment within constructed canisters (NRC Code of Federal Regulations, Part 60.111b(3), Draft 10) to 5 million years (Gera, 1975). It has been recommended that investigations of conditions that may affect the geologic repository should concentrate on geologic processes that may occur within the next 250,000 years (NRC Code of Federal Regulations, Part 60.122c, Draft 10), although it presently may be impractical to predict the occurrence of geologic processes for more than

100,000 years into the future (Bredehoeft, et al., 1978). Clearly, this wide range of containment periods can result in a wide range of recommended minimum repository depths.

The required containment time should be considered to be a function of the mechanism and consequences of waste release. The potential hazard of containment breaching depends on the radioactive intensity and concentration of the wastes. Release by slow migration along low velocity groundwater seepage paths can involve considerable dilution, adsorption, and decay of radioactive wastes before they reach the accessible environment and, consequently, 100,000 years may represent a reasonable period for required containment. However, release by repository exhumation involving direct contact of undiluted wastes with the accessible environment should be prevented for even longer time periods. An indication of the potential impact of repository exhumation can be shown by calculations presented by Bredehoeft, et al. (1978) and summarized in Table 1. It can be seen from Table 1 that if a repository containing all the solid high-level radioactive wastes estimated to accumulate by the year 2000 (a potential volume of 3000 cubic meters - Bredehoeft, et al., 1978) was exhumed, large amounts of radioactivity would be released. Even if exhumation occurred one million years after disposal, a volume of 6.4×10^{11} cubic meters of water would be needed to dilute the wastes to acceptable levels of radioactivity. This volume represents almost 40% of the global volume of water stored in river channels (Nace, 1969).

It is important to recognize that a repository could be exhumed by lateral erosion as well as vertical denudation. Retreat of cliff escarpments and lateral migration of stream valleys have been found to occur at substantial rates and to affect large areas (see Section 4 of this report). Three-dimensional isolation must be assured; thus, establishing minimum allowable repository depths below ground surface alone is not sufficient to protect against exhumation by erosion. Repository siting criteria should include minimum allowable distances from cliff escarpments, stream valley walls or other features which may be subjected to significant lateral erosion.

Prediction of the occurrence of future geologic processes involves great uncertainty (Kitts, 1976), but prediction of the rates of these potential processes may be even more uncertain (see Section 4). Stratigraphic interpretation of the maximum extent of erosion by some geologic process generally can be made with more certainty than interpretation of the rate of erosion. Consequently, because of the potentially severe impact of repository exhumation, the minimum distance of isolation from surficial erosion processes

TABLE 1 - PROPERTIES OF HIGH-LEVEL WASTES TO BE ACCUMULATED
BY THE YEAR 2000 (from Bredehoeft et al., 1978)

	<u>Accumulated by Year 2000</u>	<u>Time Elapsed Following year 2000, in years</u>			
		<u>1,000</u>	<u>10,000</u>	<u>100,000</u>	<u>1 million</u>
Radioactivity, megacuries	158,000	63.1	24.5	4.7	1.6
Inhalation toxicity m ³ air	1.2×10^{22}	3.4×10^{20}	1.4×10^{20}	1.0×10^{19}	4.4×10^{18}
Ingestion toxicity m ³ water	5.2×10^{16}	1.1×10^{13}	3.3×10^{12}	1.7×10^{12}	6.4×10^{11}

NOTE: Toxicity is defined as the cubic meters of air or water that would be required to dilute the radioactive constituents to levels specified in the Radioactive Concentration Guides (U. S. Code of Federal Regulations, Title 10, Part 20) as the maximum allowable for unrestricted use.

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should be determined on the basis of the maximum possible extent of erosion related to surficial processes that could occur in the repository area (such as glaciation or fluvial erosion). If limits can be placed on the extent of erosion at the repository site by identifying the base level elevation of erosion or analyzing the geologic history of the site, protection against repository exhumation can be assured with greater confidence.

Erosion can also uncover subsurface strata contaminated by leakage from a repository and thus expose hazardous radionuclides to the accessible environment. Although these strata would generally exhibit radiation concentrations lower than those at the repository because of dilution and dispersion during leakage, the intensity of radiation could still be significant, and the resulting impact could be compared to that produced by waste migration through groundwater to the accessible environment. Intensity of contamination in the strata would depend on the mode of subsurface migration, the volume of strata exposed to a given volume of leaked waste, and the time elapsed after waste disposal in the repository. The impact of uncovering strata with a given concentration of radionuclides would also depend on dilution of the contaminants during the exhumation process (a function of the scale and mechanism of erosion). Nevertheless, it is clear that erosion processes acting at locations other than the repository site could also reduce containment capabilities of a deep repository. The potential for exhuming strata contaminated by repository leakage should be examined by comparing the potential rates and extent of waste leakage and the possible rates and extent of erosion in the repository area within the time required for safe containment of such leakage. Repository sites should be chosen so that strata that may be exposed to leaking radioactive wastes will not be exhumed during the required containment period. Because uncovering contaminated strata would be less hazardous than uncovering the repository itself, shorter periods of isolation of contaminated strata from surficial processes may be acceptable.

3.3 Impact of Erosion and Deposition on Repository Groundwater Flow

There are many circumstances for which erosion could change the rate of waste leakage from a deep repository without actually exhuming the repository. Erosional and depositional processes continually change surficial morphology which, in turn, can affect subsurface groundwater flow. The discussion below relates how and to what degree groundwater flow can be changed by surficial processes. The influence of altered groundwater flow on repository containment is only briefly mentioned. A more detailed discussion of this impact is given in an earlier report (Geotechnical Engineers Inc., 1980).

3.3.1 Alteration of Hydraulic Gradient and Seepage Velocity

Surficial erosion and deposition can change groundwater flow gradients by altering regional topographic slopes or changing the relative elevations and locations of groundwater recharge and discharge. Regional hydraulic gradients of groundwater flow in unconfined aquifers can usually be approximated by the regional topographic slope. Processes acting to increase topographic slopes will generally increase hydraulic gradients, and flattening of regional topography will tend to decrease hydraulic gradients. Erosion and deposition effects on topography will decrease regional relief (especially in tectonically dormant areas) in long-term sequential evolution of the landscape. However, during early stages of landscape evolution local relief may actually be enhanced, depending on the amount of available relief (defined as the vertical distance between upland flats and the base level of erosion - Thornbury, 1954). Generally, if the available relief is significant, vertical erosion to the base level will increase local topographic relief and thereby increase regional groundwater flow gradients, while low available relief encourages leveling of local relief with a tendency to decrease groundwater gradients.

The stages of regional landscape evolution and, consequently, the trend toward increasing or decreasing local relief can be identified by geomorphic analysis (Bloom, 1969). The youthful phase of landscape development is characterized by steep-sided, V-shaped stream valleys oriented in dendritic patterns with high gradients. Floodplains have not yet developed, indicating that streams have not yet reached their final grade (base level of erosion). The youthful phase of development directly follows landscape rejuvenation, usually brought about by regional tectonic uplift, subsidence of the erosion base level, or change in climate (pluvial), and indicates the potential for gradual increase in local relief. The succeeding stages of development (mature stage, characterized by stream grading, floodplain formation and low gradient valleys - and an old age stage, characterized by broad, gently sloping valleys wider than stream meander belts, very low stream gradients and extensive areas eroded to base level) indicate the potential for gradual decrease on local relief. The rate of landscape development depends on many factors

and is discussed in Section 4 of this report. However, within the life of a repository, regional topographic slopes on mature and old age landscapes will tend to flatten and have a parallel effect on regional unconfined groundwater flow gradients, which could decrease the rate of waste migration from deep repositories. In contrast, topographic slopes and regional unconfined flow gradients may tend to steepen in youthful landscapes, and these landscapes should be avoided when siting a deep repository.

Changing the relative elevation or location of groundwater recharge and discharge may affect groundwater flow gradients by changing the hydraulic head difference between recharge and discharge areas or by changing the seepage path length over which the head is dissipated. These changes may be brought about most effectively by erosion concentrated at the locations of recharge or discharge. In Fig. 1A a hypothetical groundwater system is illustrated, consisting of recharge in the higher elevations by a stream. If the stream is in its youthful stage, downcutting of the stream bed will continue until the base level of erosion is achieved (Fig. 1B). This process could make the stream an area of discharge rather than an area of recharge as shown in Fig. 1B. Consequently, the distance to groundwater discharge in the accessible environment would be decreased.

As streams approach their base level, they begin to meander laterally and widen their valleys at substantial rates (see Section 4). If the river in Fig. 1B migrated toward the repository, the seepage distance between the repository and the accessible environment again would be decreased. Because the time for waste migration via groundwater is inversely proportional to the seepage distance, containment capabilities of the repository in Fig. 1B would be overestimated if they were evaluated on the basis of the hydrologic system that existed in Fig. 1A. The potential impact of erosion or deposition on the future location of groundwater recharge and discharge and the corresponding influence on groundwater flow should be considered in groundwater flow model studies used to predict the long-term migration of wastes from a deep repository.

Fig. 2 illustrates an instance where surficial processes could improve the containment characteristics of a repository. The hypothetical groundwater system in Fig. 2 consists of a dipping aquifer exposed and recharged at higher elevations and confined at lower elevations by a low permeability aquiclude serving as a repository

medium. Because of the artesian condition of the aquifer beneath the repository, groundwater leaks from the aquifer vertically upward through the repository with a velocity proportional to i_b . It will be shown in Section 4 that the rate of denudation is a function of elevation, and the peneplanation process is generally the result of erosion in higher elevations and deposition in lower elevations as shown conceptually in Fig. 2. This progression of denudation at the recharge area and deposition at the location of potential waste discharge lengthens the time for waste migration to the accessible environment by reducing the artesian head by $2\Delta h$ and increasing the seepage path length to the accessible environment by Δh . Thus, erosion can improve the containment characteristics of a repository by reducing the elevation of upland groundwater recharge areas and possibly reducing piezometric heads. Depositional processes can also improve containment characteristics by increasing the depth of burial of a repository and possibly increasing the seepage path length to the accessible environment.

Besides altering the location of existing groundwater recharge and discharge areas, surficial processes may create or destroy such areas by altering drainage patterns, creating new drainage basins or filling old drainage basins. Stream migration and stream piracy (where headward erosion of young streams intercepts and diverts previously established streams) can change drainage patterns in a relatively short time and inundate areas that were previously dry or drain areas that were previously inundated (Leopold, et al., 1964). As discussed in detail in a previous report* (Geotechnical Engineers Inc., 1980) ground surface inundation over a buried repository can significantly reduce its waste containment capabilities.

In addition to fluvial processes, deflation by wind can form depressions in loose sediments on the ground surface that flood during rainy seasons (Bachman, 1974). These basins can achieve depths exceeding 100 m (Bloom, 1978) depending on the depth of the groundwater table or bedrock and can provide new sources of recharge that may change the shape of the water table and increase the permeability of the vadose zone above the water table.

3.3.2 Erosion of Barriers to Groundwater Flow

Surficial erosion may remove or incise impermeable strata that prevent groundwater from flowing through the repository. An example of how this may occur is shown in Fig. 3. In Fig. 3A an impermeable layer of shale separates the salt dome containing a hypothetical repository from groundwater circulating in the upper aquifer. Continued downcutting of the stream to the position in Fig. 3B could provide access of fresh, circulating groundwater to the salt dome and accelerate dissolution processes threatening the stability of the repository. In other repository environments erosion of impermeable strata could permit groundwater access to subsurface strata with high permeability which border the repository, increase flow gradients, or decrease seepage path lengths through the repository. Energetic erosional processes (such as fluvial or glacial erosion) could penetrate borehole and shaft seals and thus reopen high velocity seepage paths into the repository. Design and placement of borehole and shaft seals should allow for potential degradation or removal by erosional processes. Impermeable strata that may be incised by erosion in the future should not be relied upon to contribute to long-term containment of repository wastes.

3.4 Reduction of Repository Rock Volume

Qualification criteria for radioactive waste repository site geometry generally include consideration of the minimum allowable vertical and lateral extent of the repository host rock unit (NRC, 1980; ONWI, 1980). For example, specifications for bedded salt repositories have prescribed a minimum allowable vertical extent of 61 m for the host salt unit (Brunton, et al., 1978). The minimum allowable extent of repository host rock generally is determined by the volume of the proposed repository and the width of the buffer zone of rock surrounding the repository required to dissipate mechanical effects of repository construction and thermal effects of heat released by the decaying radioactive wastes. It is important to ensure that the buffer zone will not be encroached upon by erosional processes during the life of the repository. Penetration of this buffer zone could expose fractures produced during construction that extend to the repository.

Failure to provide a buffer zone to safely dissipate thermal energy from the repository could result in excessively large thermal gradients and thermal stresses that could threaten the stability of rock surrounding the repository. The rate of thermal energy release from radioactive wastes decreases with time, however, and the buffer zone required to dissipate this energy safely also decreases with time. Fig. 4 shows the decay with time of thermal power released from reprocessed light water reactor wastes in terms of years after discharge from the reactor. In the figure it can be seen that 300 years after discharge from the reactor thermal power released from the wastes is less than 1% of that released immediately after discharge from the reactor. Thus, the buffer zone required for safe dissipation of thermal energy will decrease appreciably with time after disposal of the wastes, and the impact of long-term erosion on this aspect of containment will probably not be important. However, it is important to investigate the potential for encroachment of short-term, catastrophic erosion into the thermal buffer zone and adjust appropriately the minimum allowable lateral and vertical extent of the repository host rock.

3.5 Secondary Impacts on Repository Integrity

Surficial erosion and deposition can have minor impacts on waste containment characteristics of a repository which may not preclude an area from consideration as a potential repository site but may influence the accuracy of analytic repository models used to represent repository environments. Erosion and deposition may change subsurface stress distributions by increasing or decreasing overburden stresses differentially to alter fracture permeability in relatively shallow bedrock or threaten stability of shallow faults (Geotechnical Engineers Inc., 1980). Differential loading by erosion or deposition can maintain or increase the pressure difference responsible for salt flowage in diapiric structures (Gera and Jacobs, 1972). It has been shown that large and rapid changes in subsurface stress distributions are needed to initiate stress-dependent mechanisms that could damage a deep repository (Geotechnical Engineers Inc., 1980), and it is likely that only catastrophic erosion processes (such as glacial or fluvioglacial erosion) resulting in the rapid removal of tens of meters of overburden above the repository could measurably alter the containment characteristics of a deep repository in this manner.

Sedimentary deposition over a repository generally will have only minor deleterious effects on a deep repository and in many cases will improve the ability of the repository to isolate wastes from the accessible environment. Deposition over a repository will tend to increase the depth of the repository and, consequently, tend to increase the waste migration path length. This will be a favorable

impact, providing that subsidence will not place the repository at such extreme depths that high overburden stresses and geothermal gradients will adversely affect the rheologic properties of the repository rock (i.e., increasing the potential for rock melting or plastic behavior leading to diapiric movement) within the required containment period.

Rapid deposition may have a detrimental impact on short-term (in terms of tens of years - Environmental Protection Agency, 1978) remote monitoring of wastes emplaced in a deep repository, and, for this reason, repository sites should avoid areas presently subject to catastrophic rates of deposition (such as floodplains), or monitoring systems should be designed to operate under such adverse conditions.

4. EROSION PROCESSES RELEVANT TO WASTE CONTAINMENT IN DEEP GEOLOGIC REPOSITORIES

4.1 Introduction

Estimates of the future depth of penetration of surficial erosion at a particular site usually are included in the evaluation of the long-term impact of geologic processes on a deep repository. Typically, these estimates are obtained by multiplying the present measured rate of denudation in the region containing the repository site by the length of time required for safe containment of the waste or by interpreting the maximum magnitude of erosion that has occurred in the past at the site by examining the geologic record. Measured rates and interpreted magnitudes of erosion depend on a number of variables which contribute large uncertainty to the results. The error that can result from inappropriate consideration of these data could influence decisions regarding repository siting. The following discussion covers identification of the factors controlling the rate and depth of contemporary and future erosion processes, investigation of the uncertainties in presently accepted measurement and interpretation techniques, and suggestions as to how data obtained by these techniques can be used to develop screening criteria for potential repository sites.

4.2 Regional Denudation

4.2.1 Factors Affecting the Rate of Denudation

Measured rates of regional denudation (the leveling of continental surfaces by weathering and erosion) have been examined in preliminary feasibility studies to compare the impacts that erosion may have at potential repository sites (Gera and Jacobs, 1972). Some studies have extrapolated these rates into the future to determine the minimum depth of a repository required to prevent exhumation within a given time period (Lyons, 1971). However, because the rate of denudation depends on many factors, including climate, topography, type of surface material and time, extrapolation into the future is tenuous, and only qualitative comparisons of present rates can be made with confidence.

The data usually referenced to indicate the relative magnitudes of erosion in major drainage basins in the United States were obtained by Judson and Ritter (1964), and some of these data illustrating the wide range of measured denudation rates are given in Table 2. This range could be due partly to differences in environmental and geologic conditions among the basins and the length of time during which the measurements were made. In their paper, Judson and Ritter used these rates to estimate the rate at which the continental United States is being denuded, and they extrapolated this rate (obtained by averaging the regional rates in Table 2) to future time, assuming that the present rate was correctly determined and was independent of time. The authors conceded that although the regional erosion rates may indicate an average rate of denudation for the continent, they cannot be applied to any local area to obtain an estimate of the local rate of erosion.

The ultimate depth of denudation in a region by fluvial processes depends on the elevation of the erosion base level, which is an imaginary surface below which streams cannot erode. The ultimate base level is sea level, but in the interior of continents, natural surficial processes may establish temporary local base levels that will be effective for millions of years. The rate of regional denudation can give an indication of the possible rate of change of a temporary base level and can be helpful for determining the minimum required repository depth, which should place the repository below the elevation of the lowest base level that will prevail at the repository site during the required period of waste containment. In order to evaluate qualitatively how rapidly a temporary base level may change and determine if the ultimate base level (sea level) should be used as a datum for the depth of a repository, the following characteristics of the region near the repository should be examined (Woodward-Clyde Consultants, 1977): climate, topography and relief, surface characteristics, and geometry of the drainage basin.

Longbein and Schumm (1958) investigated the influence of climate on the rate of erosion and concluded that the rate of erosion depended not only on the direction of climate change (i.e., precipitation increase or decrease), but also on the climate before the change. By measuring the rate of sediment accumulation in reservoirs, Longbein and Schumm developed a relation between the effective

TABLE 2 - SUSPENDED SEDIMENT LOADS BY INDIVIDUAL STREAM
BASINS (from Jadson and Ritter, 1964)

Region and River	Drainage Area mi ²	Period of Time For Records years	Erosion Rate cm/1000 years
North Atlantic			
Delaware	6,780	8	2.0
Schuylkill	1,893	10	6.9
Scantic	98	5	1.0
Rappahannock	616	7	1.8
South Atlantic and Eastern Gulf			
Roanoke	1,802	4	3.3
Yadkin	2,280	6	4.6
Alabama	22,000	8	1.3
Western Gulf			
Colorado	30,600	7	1.5
Rio Grande	26,770	9	4.6
Pecos	3,970	9	9.1
Mississippi			
Mississippi	1,243,500	12	3.3
Colorado			
Colorado	137,800	32	14.2
Pacific Slopes in California			
Sacramento	27,500	4	1.3
Bel	3,113	3	77.2
Mad	485	13	49.0
San Joaquin	14,010	4	0.3
Columbia			
Snake	103,500	2	1.8
Columbia	102,600	2	1.3
Green	230	4	4.1

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precipitation and the annual sediment yield, which reflects the rate of erosion in the drainage area of the reservoir. However, the influence of vegetative cover influenced the results, as shown in Fig. 5. Wolman (1967) and Gera and Jacobs (1972) showed the significant effect of land use on the rate of erosion in a given region with a constant climate, indicating increased vegetative cover decreases the rate of surface denudation (see Fig. 6 and Table 3). Thus, although Langbein and Schumm (1958) showed that regions with annual precipitation rates of 25 to 35 centimeters may exhibit the maximum rates of erosion, this concept is not true in general, and with a constant type of vegetative cover or land-use pattern, an increased rate of precipitation will tend to increase the rate of erosion. Consequently, when considering future rates of regional denudation, the correspondence between precipitation rates and vegetative cover for the repository region should be understood before applying the relationships shown in Figs. 5 and 6 and Table 3.

The rate of denudation depends on the surficial lithology in addition to the vegetative cover. Denudation rates in erodable materials, such as weathered shale or loose sediments, have been measured to exceed 13 m/1000 years in small drainage basins, while denudation rates in unweathered, competent bedrock rarely exceed 92 cm/1000 years, which Schum. (1963) suggested as an upper-bound average rate for regional denudation in competent bedrock. With regard to mechanical resistance to erosion, Young (1969) reported no marked difference between igneous, metamorphic, or siliceous limestone rocks, but he added that unconsolidated sediments or poorly cemented rock may exhibit denudation rates 10 to 1,000 times greater than those for the above rock types under similar conditions.

Resistance to chemical dissolution can vary substantially among bedrock lithologies. Bachman (1974) estimated that the dissolution rate for exposed bedded salt in semi-arid southeast New Mexico averaged 15.2 cm/1000 years over the past 600,000 years, a period which included several pluvials (periods of abnormally high rates of precipitation). During that time span the dissolution rate probably varied significantly from the average rate, and it is likely that future denudation rates would also vary with precipitation rates. For example, some recent

TABLE 3 - VARIATIONS OF DENUDATION RATES WITH
LAND-USE AND VEGETATIVE COVER
(from Gera and Jacobs, 1972)

<u>Land Use or Cover Type</u>	<u>Average Annual Rainfall (cm)</u>	<u>Average Annual Runoff (cm)</u>	<u>Average Denu- dation Rates cm/1000 years</u>
Open land:			
Cultivated	132	41	185
Pasture	130	38	14
Forest land:			
Abandoned fields	130	18	1.1
Depleted hardwoods	130	13	0.9
Mature pine hardwoods	137	3	0.2
Gullies	135	-	1,570

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rates of horizontal dissolution in surficial salts in the Southern High Plains of Texas have been measured locally to exceed 5 cm/year and have been estimated to average about 17 m/1000 years. In contrast, the dissolution rate of sedimentary rock (predominantly sandstone) in the Colorado River basin may be as low as 0.9 cm/1000 years (Judson and Ritter, 1964). Thus, if a region consists of surficial lithologies with widely varying resistances to erosion, the average rate of denudation for the region may differ substantially from local rates, and interpretation of the permanency of temporary local base levels may be difficult. Moreover, if vertical lithologic variations cause differences in erosion resistance with depth, the rate of denudation in the future may dramatically change from the present rate as the buried lithologies are exposed. Therefore, predicting future rates of regional denudation should consider both horizontal and vertical lithologic variations in a region.

Topography and relief have been shown to be important factors affecting denudation rates, and these factors contribute to the time variant behavior of denudation. Ruxton and McDougall (1967) related the rate of denudation in dissected lavas in New Guinea independently to relief, gradient and slope length, and these data are shown in Fig. 7. Ruxton and McDougall also found a close correlation between altitude and denudation rate (see Fig. 8) and developed the following empirical expression:

$$x = 0.7087y^{0.6318}$$

where, x = denudation rate (cm/1000 yr)

y = altitude (m)

It is evident that relief, gradient and slope length are not independent variables; thus, comparisons between the relations shown in Fig. 7 are not meaningful statistically. It is probable that multivariable regression of a number of independent factors affecting erosion (such as topography, precipitation, and lithology) would provide a more general quantitative relationship between denudation rate and environmental characteristics. Consequently, the results presented by Ruxton and McDougall are applicable to their specific region of study only and should be viewed to indicate qualitatively how erosion rates depend on topography.

As denudation continues with time, topography is leveled and the ground surface elevation approaches the base level of erosion. Consequently, the denudation rate also decreases with time. If the above expression is integrated between a given altitude and the ultimate base level elevation in the region for which the expression was developed, the time required to erode the ground surface from the given altitude to base level can be calculated. The results of this calculation performed by Bloom (1978) and shown in Fig. 9 supports the concept that the rate of denudation decreases with time. However, the figure also shows that the rate remains nearly constant until the relative altitude with respect to base level is nearly halved (during a corresponding time interval of approximately 1.5 million years in the region of study), after which the denudation rate rapidly decreases. Thus, if the relationship between denudation rate and altitude with respect to ultimate base level obeys a similar law in other regions (and other factors such as climate, land use, and lithology exposed to erosion remain constant), contemporary denudation rates will tend to decrease initially at a slow rate and may be essentially constant for long periods of time. If the potential long-term changes in temporary base levels of erosion in a region are evaluated using modern denudation rates determined on an acceptable statistical basis and other factors remain constant, the error in the resulting estimates may be acceptable and will usually be conservative.

Corbel (1959) expanded his studies of regional denudation to include the combined influence of topography and climate. Bloom (1978) presented the results by categorizing lowlands as regions with slopes less than 0.001 and mountains as regions with slopes greater than 0.01. The data presented in Table 4 show that differences in topography generally will have a greater influence on the denudation rate than differences in climate, but complex interaction between these two factors prevents the development of correlative relationship with the available data. The present state-of-the-art is not sufficiently developed to permit other than qualitative assessments of future denudation rates when multiple factors are considered.

Tectonic movements and sea level fluctuations can either accentuate typical time-variant trends of denudation rates or reverse them. Tectonic uplift will increase available relief and will increase the rate of denudation, while subsidence may have the reverse effect. Studies of the

TABLE 4 - COMPARISON OF DENUDATION RATES
IN VARIOUS CLIMATES
(from Corbel, 1959)

<u>Regional Climate</u>	<u>Denudation Rate</u> <u>cm/1000 years</u>
Lowlands: Slope less than 0.001	
Climate with cold winter	2.9
Intermediate Maritime climate	2.7
Hot-dry climate	1.2
Hot-moist climate	3.2
Equatorial climate	2.2
Mountains: Slope greater than 0.01	
Semihumid periglacial climate	60.4
Extreme nival* climate	80.0
Climate of Mediterranean high mountain chains	44.9
Hot-dry climate	17.7
Hot-moist climate	9.2

*Regions with "nival" climates are characterized by long periods of snow cover.

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relative rates of erosion and tectonic movements (Schumm, 1963) show that tectonic movements occur more rapidly than erosion, and uplift can continue to increase available relief and denudation rates with time. Moreover, potential repository host rock presently located beneath the base level of erosion could be uplifted above the ultimate base level and become exposed to surficial erosion. Repository sites should avoid regions of tectonic uplift which will increase erosion rates and the ultimate depth of erosion in the future. A repository placed in a region undergoing tectonic uplift should be placed at sufficient depth to ensure that it will remain below the base level of erosion during the required waste containment period.

Fluctuating sea levels can influence the rate of erosion by altering the elevation of the ultimate base level. An earlier report (Geotechnical Engineers Inc., 1980) summarized the potential range of sea level fluctuations within the next 100,000 years and concluded that in the future the apparent sea level could decrease as much as 130 m below the present sea level. In order to ensure that a repository will remain below the ultimate base level of erosion and will be protected permanently against exhumation by future denudation, repositories and accompanying buffer zones sited in areas where the base level is determined by sea level elevation should be buried at least beneath the lowest probable future sea level elevation.

4.2.2 Measurement and Interpretation of Denudation Rates

Four basic methods are available for estimating the rate of surface denudation by erosional processes:

- a. Measurement of suspended and dissolved solids in the sediment load of streams and correlation with stream discharge records over a specified time period.
- b. Measurement of the volume of sediment deposited in reservoirs or on continental margins during a known or interpreted time period.
- c. Examination of landform or stratigraphic changes produced by erosion and identified to have occurred within dates determined by geological interpretation or radiocarbon dating (this method could include measurement of degradation of historical monuments with time).

d. Measurement of surface erosion on slopes by surveying and leveling techniques.

Each method has been used to generate data referred to in Section 4.2.1, and it is important to understand the uncertainties inherent in these techniques and the assumptions required to obtain estimates of future denudation from data obtained by these methods.

Most data presented in the literature on rates of regional denudation (including those given in Tables 2 and 4) have been obtained by Method a. Stream samples collected at regular intervals (typically over a time span of 1 to 10 years) are measured for sediment load concentrations, and these concentrations are multiplied by the volume of stream flow to obtain the volume of sediment discharged by the river. This volume is then divided by the surface area of the drainage basin to estimate the average amount of vertical denudation. It is clear that considerable error can result from gross calculations of stream flow and drainage basin area, but other conceptual problems add to the uncertainty in these estimates.

Trimble (1977) discovered that the sediment yield at the mouths of major rivers had better correlation with stream channel efficiency, basin morphology and local channel and bank erosion than with lithology, climate, vegetation or land use. Judson (1976) noted that under similar conditions, small basins yielded 2 to 3 times more sediment per unit area than large basins. Both of these studies indicated that the ability of the stream to transport sediment in addition to the erodibility of the landscape was an important factor controlling the sediment load. Comparison of measurements of soil loss in drainage basin uplands to sediment yields at the mouth of the basin by Trimble (1977) showed that the denudation rate calculated by sediment load was only 6% of the rate indicated by upland soil loss. Thus, especially in large basins, sediment storage within the basin and stream system appears to be much greater than sediment yield by the stream and local erosion rates may significantly exceed the average rate obtained by measuring stream sediments.

Extrapolation of denudation rates measured over a limited time span to thousands of years into the future adds to the uncertainty of projected erosion depths. Studies of stream flow by Leopold, et al. (1964) showed that in major rivers in the western United States, the majority of sediment load yielded by the rivers occurred during

floods with return periods often exceeding ten years. Thus, denudation rates based upon stream measurements made over short time periods cannot give useful results. This was verified by Gerson (1976), who also failed to obtain meaningful correlations between stream sediment yields measured for one year and environmental characteristics, such as lithology, catchment area, and rainfall intensity. The aperiodic behavior of floods also makes it impossible to extrapolate with confidence sediment yield measurements made during time spans including flood episodes.

Future land use by man, which may be the most important factor controlling future erosion ration, also cannot be predicted. In fact, recently measured denudation rates have dramatically increased due to agricultural land use by man, and this trend is expected to continue in the future (Judson, 1976).

Measurements of denudation rates indicated by deposited sediments are subject to many of the uncertainties described above. However, additional uncertainty is introduced by estimating the volume of sediment deposited at the mouth of a drainage basin over a measured or interpreted period of time rather than directly measuring the sediment load in streams (Gilluly, 1964). Volumes of deposited sediments can be only crudely estimated and interpretation of the age of the sediments can be made with only limited accuracy and can lead to significant error in the calculated denudation rate. It is also possible that much of the sediment load carried in solution was not deposited at the basin mouth, or a considerable volume of sediment was eroded and carried away by deep-water currents. For purposes of comparing erosion rates in different drainage basins, direct measurement of sediment load is generally preferred over estimating deposited sediment volumes.

Data presented in Figs. 7 and 8 were obtained by interpreting the probable magnitude of landform or stratigraphic changes. Estimating the rate of surface denudation by this method involves the greatest amount of geological interpretation of the four methods and potentially the most uncertainty. In order to estimate denudation rates by this method, the original shape and thickness of the landform or stratigraphic formation before erosion must be assumed, and erosive processes are assumed to have occurred at a uniform rate starting immediately after completed formation of the geologic deposit. These assumptions neglect the possibility of extensive periods

of protection from erosion and the possibility of catastrophic variation of erosion rates, which have been observed in studies of modern geologic processes. This could have important consequences on selecting the location of a repository. For example, if a basalt flow found at some locations to be 200 m thick is found to be locally eroded to a thickness of 20 m and overlain by a subsequent lava flow which was emplaced 100,000 years after the former flow occurred, then the denudation rate would be calculated to be 1.8 m/1000 years. However, if a catastrophic episode of erosion had actually eroded the basalt in 1,000 years and the basalt was then protected from erosion until the overlying flow was deposited, the true rate of erosion related to the actual erosive process would have been 100 times greater than the interpreted rate. The likelihood of this type of error is enhanced if longer time periods are considered when averaging the denudation rate. For example, the denudation rate of the White Mountains in California interpreted from the exposure of tree roots of Bristlecone Pines during the past 4,000 years (La Marche, 1968) was 100 times that interpreted from erosion of basalt flows averaged over a period of 10 million years (Marchand, 1971).

The fourth method described above involves short-term measurement of slope erosion at localized areas. Attempts have been made to correlate the rate of slope erosion to environmental conditions by using this method and carefully choosing the study areas on a statistical basis. After conducting such a study for approximately one year, Lam (1977) concluded that there was no statistically meaningful correlation between local slope erosion rates and environmental factors. Lam believed that because each localized site was not functionally independent or isolated, erosion of a larger system (possibly the drainage basin) was more dependent on environmental factors. Richter and Negendank (1977) supported this observation in a 5-year study in the drainage basin of the Moselle River in Germany. Nevertheless, it is possible that the short time span of these studies was the primary reason for the lack of correlation. Although such methods used on steep slopes in loose materials may give upper-bound rates of short-term, local erosion, they are not applicable for determining denudation rates over long periods of time.

4.3 Slope Retreat By Mass Wasting

In the preceding section, slope erosion by fluvial processes, runoff from precipitation, and dissolution were discussed, and some average rates of erosion were given. On steep slopes mass-wasting by gravity is also an important process. Because this type of erosion acts primarily in the horizontal direction (especially if the slope angle is greater than 45°), the impact of this process on the lateral extent of repository host rock should be considered if the depth of the repository will be less than the depth of the base of nearby slopes or cliffs.

Mass-wasting processes can consist of creep in rock or soil, landslides, or rockfalls. The rates of these processes are a function of the slope angle and height, the type of material composing the slope, and climate. Creep occurs at such a slow rate and involves such shallow movement that this process probably would have no impact on the lateral extent of repository host rock. Landslides and rockfalls can involve large volumes of material and can cause rapid retreat of slopes which may significantly reduce the extent of repository host rock.

Landslides in soil often occur on slopes that have been oversteepened by some local erosive agents, such as waves, rivers or glaciers. If the strength of the soil cannot resist gravity forces, or some environmental processes occur that reduce the strength of the soil, soil will move downslope until the slope reposes at an angle compatible with the strength of the soil. After this has occurred, the slope is "stable" and will no longer have a tendency to slide, unless erosive forces once again increase the slope angle or environmental processes further reduce soil strength. However, because repositories are likely to be placed in rock, landslides in soil will also not have a significant impact, and rates of slope retreat determined from landslides in soil should not be used to determine the allowable lateral extent of repository host rock.

Rock slopes and cliffs can also exhibit rapid rates of retreat. Cliffs and talus slopes are often structurally controlled by joint and bedding plane weaknesses, but they can also be cut by rivers and glaciers. The persistence of slope angles is related to the weathering character of the rock and climate (Bloom, 1978). As the rock weathers and weakens, it can no longer maintain the slope angle and it succumbs to gravity forces, subsequently revealing a fresh rock face that will also eventually weather and fall. Cliffs can be quickly covered by their own talus and protected against further weathering unless erosion removes the talus debris from the base of the cliff.

Cliff erosion does not normally occur at a uniform rate. Rock-falls and slides occur in a catastrophic manner and involve movement of large volumes of material during short periods of time separated by much longer periods of inactivity. The physical extent of each slide or fall depends on the depth of weathering into the rock face, structural control of zones of weakness, and the pre-existing slope angle. Unusual events such as earthquakes can decrease stability and trigger larger than normal rockslides. Average rates of mass-wasting are usually estimated by Method c. described in Section 4.2.2 and, as previously discussed, this method can produce significant errors in interpreted future rates of erosion.

Mesozoic-aged sandstone cliffs on the Colorado Plateau were estimated by Schumm and Chorley (1964) to have retreated approximately 9 m by rockfall during the last 2500 years (3.6 m/1000 yr). However, as Bloom (1978) pointed out, these cliffs had been exposed to weathering for a long period of time before movement began and this rate may be excessively high if applied to longer time periods. If the erosion rate was estimated by averaging the rate of widening of the Grand Canyon during the past 20 million years, a rate of only 0.3 m/1000 years would be interpreted.

Studies of slope retreat in the cold maritime climate of Sweden (Rapp, 1960) showed that rockfall in schist and limestone triggered by seasonal freezing and thawing yielded a rate of retreat between 0.04 to 0.2 m/1000 years.

An extensive review of the literature published on rates of slope retreat by Bloom (1978) concluded that steep valley walls or cliffs retreat at rates between 0.1 m to 3 m/1000 years in a variety of climates and diverse lithologies. These rates may be useful for determining the minimum allowable lateral extent of repository host rock that may be subjected to mass-wasting processes during the required period of waste containment.

4.4 Fluvial Erosion

Stream valleys are incised at locations where fluvial processes have eroded the landscape most effectively. Present siting criteria require that repositories avoid the 100-year floodplains of rivers to prevent adverse hydrologic conditions from affecting operation of the repository (NRC, 1980). Although this criterion may protect the repository from fluvial erosion in the short term, stream valleys can migrate laterally over areas much larger than the 100-year floodplain in the long term, and catastrophic alteration of drainage patterns can produce streams in areas previously isolated from fluvial erosion. Thus, satisfying the above criterion does not preclude the possibility of fluvial erosion concentrated in stream valleys at a repository site. It is important to recognize the factors influencing

the rate and depth of erosion in stream valleys and to appreciate the potential for valley migration and relocation. The following discussion examines the aspects of fluvial erosion and gradual valley migration relevant to repository integrity and site selection. Catastrophic relocation of stream valleys and alteration of drainage patterns by glacial processes are examined in Section 4.5.

The rate and magnitude of fluvial erosion basically depends on the stream-flow velocity and the resistance of stream bed material to erosion. Stream-flow velocity indicates the energy available for erosion and is a function of gradient (reflecting gravity potential), channel geometry and roughness, precipitation, and concentration of suspended sediments (Leopold, et al., 1964). Gradients can vary with location in the stream valley (with higher gradients generally occurring near the headwaters and lower gradients occurring near the stream mouth) and with time (as erosion gradually reduces the bed elevation to the base level over a large portion of the stream). Consequently, on the basis of gradient variations alone, measurements of valley downcutting rates made at specific locations in the stream cannot be extrapolated into the future without considerable error and cannot be applied contemporaneously to other locations in the valley.

Channel geometry and roughness can produce significant variations in stream-flow velocity. Formulae used to estimate the mean flow velocity in engineering calculations employ empirical coefficients to account for energy loss due to bank friction and irregular flow. In Manning's equation, an empirical factor has been developed to relate proportionally mean flow velocity in natural stream channels to such factors as vegetation, channel curvature and other obstructions. Values chosen for this factor vary by over an order of magnitude and have a corresponding influence on the calculated velocity. However, Leopold, et al. (1964) state that because of the infinite variety of channel boundary conditions and materials, flow resistance cannot be quantitatively specified in this manner for a given stream. Moreover, future channel modifications cannot be predicted because of the complex interaction of environmental conditions and fluvial processes, neither of which can be specified uniquely or quantitatively assessed.

Floods resulting from increased precipitation can increase average stream-flow velocities to values normally ranging from 90 to 180 cm/sec in most streams and can produce local velocities measured as high as 600 cm/sec (Leopold, et al., 1964). These high velocities can increase the rate of erosion so drastically that the majority of downcutting during the life of a stream may be concentrated during relatively short periods of flooding. The erosion potential of a single episode of flooding is usually evaluated in terms of the depth of scour measured or observed during historically recorded flood events. Scour can be measured by embedding scales in the channel bottom that can measure changes in the channel floor elevation or by ob-

serving denudation of bed material adjacent to submerged structures, such as bridge piers. Some examples of scour depths measured or observed in rivers with a variety of bed materials are given in Table 5. Studies of scour during annual flash floods in ephemeral streams in semi-arid climates have shown that the depth of scour in sandy stream beds averaged between 0.15 and 0.3 times the average channel width (Gerson, 1977). Other investigations have shown that depending on the channel and bed material characteristics, floods may have little impact on channel geometry. In many cases where the stream bed consisted of bedrock, individual historically-recorded floods had no measurable effect on the stream bed elevation (Leopold, et al., 1964). Moreover, in sandy materials, deposition following scour during flood episodes often results in no net change in stream bed elevation, and subsequent floods actually rework the same materials and do not progressively erode the channel bottom below the depth of initial scour (Leopold, et al., 1964).

The ability of a stream to erode its bed is a function of its sediment load concentration as well as its velocity. At a given velocity, a stream with a substantial concentration of suspended sediment is less able to pick up additional sediments by bed erosion than a stream with no suspended load (Dunbar and Rogers, 1957). Once fully loaded with sediment obtained from erosion upstream, further channel erosion downstream may not be possible, and deposition will probably occur as the gradient and velocity decreases. Sheet runoff during heavy precipitation may actually overload the stream so that deposition rather than scour is the net result.

The erosion resistance of the stream bed material may be the most important factor limiting the rate and depth of erosion. If the shear strength of the bed material exceeds the shear force applied by water flow, the bed will not erode. Hjølström (1939) related the particle size of loosely-deposited, uniform sediments to the potential for erosion by water flowing at a range of velocities to show the resistance of uncemented sediments in stream beds to channel downcutting. His data showed that cohesion in fine-grained sediments can provide considerable resistance to erosion, and erosion resistance increases with the increased friction resistance of heavier, coarse-grained sediments. It is important to note that Hjølström's studies neglected the influence of compaction and nonuniform gradation on erosion resistance and, thus, his results are not directly applicable to typical soil deposits. However, his results do indicate that stream-flow velocities exceeding 200 cm/sec (the upper range of average flood flow velocities) will erode most soil deposits and transport sediments as large as cobblestones (approximately 10 cm in diameter). When the bed material consists of bedrock, the rate of channel downcutting will be relatively low and, in some cases, highly resistant bedrock may prevent channel downcutting during normal stream flow.

TABLE 5 - SELECTED DATA ON DEPTH OF SCOUR
OBSERVED IN VARIOUS RIVERS
 (from Leopold, et al., 1964)

<u>Maximum Depth of Scour Below Normal Bed Elevation (meters)</u>	<u>River Bed Material</u>	<u>Source of Data</u>
3 to 4.5	Silt, gravel	Pacolet River
6.8	Sand, gravel	Colorado River (U. S. Bureau of Reclamation, 1950)
39	Sand, gravel cobble	Black Canyon, Colorado River
9.8	Cobble, boulders	Canadian River at Eufaula Dam
12.3		Rio Grande, New Mexico
3.7 to 4.6	Sand and gravel scoured to bedrock	Yellow River
6.2	Very fine sand	Colorado River. Yuma, Lane and Borland (1954)

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However, the potential for bedrock erosion exists during catastrophic flooding with extremely high stream-flow velocity (much greater than 200 cm/sec).

Studies of natural river channel migration and the formation of floodplains have shown that rivers can migrate laterally over large distances at substantial rates within the valley. Some typical rates and extents of lateral migration are given in Table 6.

Lateral migration of rivers begins when the lateral resistance of the channel banks is less than the resistance of the channel floor, or stream-flow velocities resulting from flow around obstructions exceed stream-flow velocities resulting from the downstream gradient, so that the rate of bank erosion exceeds the rate of bed erosion. When lateral migration of a river section becomes significant, the river has usually either reached its base level of erosion at that section or has eroded its bed to a highly resistant material (i.e., bedrock). Consequently, continued downcutting of the channel, except for scour and fill during floods, will be minimal (Leopold, et al., 1964). Because a river will normally have the ability to migrate over its entire floodplain, a repository buried beneath the floodplain (regardless of the flood recurrence interval corresponding to that floodplain) should be placed at least below the maximum depth of scour of the river bed to prevent exhumation and at sufficient depth so that such scour will not damage the waste containment capabilities of the repository.

Because of the many uncertainties in predicting future landscape alteration by observing contemporary fluvial processes, efforts have been made to interpret geologically the past development of fluvial systems within the region containing a potential repository site. The impact of similar development in the future is then evaluated for the potential repository. A study (AEC, 1971) was made to examine the geologic history of fluvial erosion in the Arkansas River basin to predict the potential impact of future fluvial erosion at a hypothetical repository in the region. The study indicated that since the Arkansas River had incised bedrock to a depth of 62 m during the past one million years, new streams that may form above the repository and be subjected to the same geologic processes that occurred in the past could incise bedrock to the same depth in the next one million years, and the Arkansas River could erode its basin to an additional depth of 62 m during the same time period. Thus, it was concluded that a repository located in a bedded salt deposit 250 m below ground surface (or at Elevation +300 m with respect to mean sea level) would be protected against the detrimental effects of fluvial erosion. Although these studies showed that repository exhumation by future fluvial erosion was unlikely, permanent isolation from fluvial processes could not be ensured for the proposed repository because of its location above the ultimate base level of erosion.

TABLE 6 - RATES AND EXTENTS OF LATERAL MIGRATION
OF RIVERS ACROSS VALLEYS
(from Wolman and Leopold, 1957)

River and Location	Drainage Area	Extent of Lateral Movement	Period of Measurement	Rate of Movement
	(sq km)	(m)	(yrs)	(m/yr)
North River - Parnassus quadrangle, Va.	132	126	50	2.5
Laramie River - Fort Laramie, Wyo.	12,100	31	103	0.3
Colorado River - Needles, Calif.	450,300	1,170	39	30
Yukon River - at Kayukuk River, Alaska	845,000	1,690	170	10
Yukon River - Holy Cross, Alaska	845,000	740	20	37
Mississippi River - Rosedale, Miss.	2,900,000	732	15	49
Missouri River - Peru, Neb.	132,000	1,540	20	77

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Repositories sited in uplands beyond the extent of present fluvial floodplains are not guaranteed long-term protection from exhumation by fluvial processes unless they are buried beneath the erosion base level, often approximated by the floodplain elevation (unless fluvial development is limited by a local, highly resistant geologic deposit). Thus, to ensure permanent isolation from fluvial erosion, the acceptable elevation of a repository horizon may be the same for a repository located in uplands beyond the extent of present floodplains and a repository buried beneath an active floodplain. Consequently, for the purpose of permanent protection against fluvial erosion, acceptable repository sites may be more easily located in tectonically stable areas that are presently eroded to near sea level elevation.

4.5 Glacial and Fluvio-glacial Erosion

During periods of continental glaciation in the United States, the landscape was catastrophically altered by glacial and fluvio-glacial erosion. Price (1973) speculated that the erosive effects of a glacial advance was 10 to 20 times greater than fluvial erosion during an interglacial. Erosion during glaciation originated from two primary sources: scouring under advancing continental ice sheets and fluvial erosion by catastrophic release of meltwater impounded behind and within glaciers. Although the maximum depth of erosion by outbursts of glacial meltwater was limited by the apparent sea level existing during glaciation, the depth of erosion by glacial scouring extended well below sea level elevation at several locations. Therefore, it is important to understand the mechanics of glacial scouring in order to evaluate if this agent of erosion will control the allowable minimum depth of a deep radioactive waste repository in areas that may be subjected to future glaciation.

4.5.1 Glacial Scouring

Erosion at the base of a glacier is produced by abrasion and quarrying action of the ice on the overridden ground surface. Quarrying consists of the actual gripping and removal of loose sediments and weathered or fractured rock by ice and can erode basins of considerable depth. Abrasion results from the scraping of the ground surface by debris carried at the base of a glacier, producing relatively shallow erosion features. Abrasion has been observed to be the dominant erosive process in competent bedrock resistant to ice quarrying, and normally grooves and striations in the bedrock surface extend to a depth of 1 to 2 m (Flint, 1957). However, in Canada some grooves have been observed to extend to a depth of 40 m below the bedrock surface (Price, 1973).

The depth of abrasion by glaciers appears to be dependent on the thickness and velocity of the glacier, the concentration and hardness of the debris carried by the glacier, and the hardness of the overridden bedrock (Boulton, 1974). Studies of contemporary alpine glaciers indicate that glaciers with thicknesses exceeding 25 m (all other conditions being equal) will have the same abrasion potential (Price, 1973); thus, thickness is probably not a limiting factor on abrasion by continental glaciers. Boulton (1974) developed a semi-empirical equation to calculate the rate of abrasion given the relevant properties of the glacier, transported debris, and bedrock. Although the hardness of the debris and bedrock can be quantified with some confidence, it has been shown that debris concentrations and glacier velocity can vary unpredictably. Consequently, rates calculated by this semi-empirical method serve only to illustrate qualitatively the abrasion potential of a glacier. Rates of abrasion measured beneath modern glaciers combined with geologically preserved evidence of glacier grooves and striations may be more useful for predicting the impact of future glacial abrasion on the landscape.

The ability of the glacier to erode the landscape by quarrying is also a function of glacier velocity and thickness and the resistance of the overridden ground surface. Quarrying will tend to occur in areas where surface materials are relatively loose and the topography encourages high-velocity glacial flow that produces large tensional stresses permitting "plucking" of fractured rock. Valleys parallel to the direction of glacier advance located upstream from the postglacial margins experienced deep erosion because of repeated, high velocity advances of the glacier front and the presence of rock-weakening joints extending deep into valley walls and floors. In contrast, areas of low relief downstream from uplands trending perpendicular to the direction of glacial advance (which effectively reduced the velocity of the glacier) experienced only shallow erosion (Flint, 1957). Evidence of repeatability of glacial movement during the numerous advances in the Pleistocene (Flint, 1957) indicates that future advances may parallel these movements and, unlike glacial abrasion which is a localized phenomenon, glacial quarrying producing deep erosional basins may be more predictable.

Estimates of the depth of glacial scouring have been made by two methods: measurement of contemporary glacier erosion rates and extrapolation of these rates over a speculated span of future glaciation, and comparison of the difference between interpreted preglacial morphologies and existing postglacial erosional remnants.

The rate of abrasion under modern glaciers has been examined at discrete locations by measuring the rate of surface lowering of metal or rock plates anchored flush with bedrock at the front of seasonally fluctuating glaciers (Boulton, 1974). The thickness of the plate is measured precisely before it is embedded at the front of a glacier during the seasonal stage of maximum recession and is remeasured after subsequent advance and recession of the ice sheet. Measurements on basalt and marble plates under glaciers in Iceland (Boulton, 1974) showed average abrasion rates of 1 mm/year and 3 mm/year, respectively. Abrasion rates up to 36 mm/year were measured under four glaciers, and these rates were found to vary in consecutive seasons of advance. Although these measurements contributed to the understanding of abrasion at the bases of glaciers, they are not useful for projecting future depths of glacial abrasion because of the uncertainty of the time span of future glaciation and the inability of these measurements to account statistically for the many variables affecting the rate of abrasion.

The rate of glacial scouring (by abrasion and quarrying) has been estimated by measuring the concentration of debris transported by meltwater streams emerging from glacier ice fronts. Applying this method to cirque glaciers with small erosional basins, Andrews (1979) obtained the following rates of erosion:

volcanic rocks in Antarctica	0.3 m/1000 years
Mount Rainier, Washington	1.1 m/1000 years
Colorado Front Range	2 m/1000 years
Baffin Island, Alaska	0.05 m/1000 years

By collecting data on erosion rates of alpine glaciers in maritime climates, Derbyshire (1979) concluded that wet-based glaciers (glaciers that flow over the ground surface on a sheet of meltwater) are more erosive than cold-based glaciers (glaciers that are frozen to the ground surface). This conclusion may not be generally true, for quarrying action is enhanced in cold-based glaciers. Derbyshire assigned representative erosion rates of 0.5 to 5.0 m/1000 years for wet-based glaciers and 0.05 m/1000 years for cold-based glaciers.

It is clear that this method of measuring erosion by glaciers does not yield results that are relevant to long-term continental glaciation. Because it is important to be able to estimate accurately the total volume of meltwater exiting from a glacier, normally glaciers with small drainage basins (such as alpine valley glaciers) are examined. The rate of erosion of such glaciers will differ from that of a continental glacier because of differences in ice thickness and flow velocity, and it is likely that alpine glaciers will exhibit higher rates of erosion because of their relatively high flow velocities. Moreover, meltwater exiting from the base of a glacier probably is only a fraction of the total volume of meltwater produced by a glacier. Studies of modern glaciers (see Derbyshire, 1979) have shown that glaciers often contain lakes and rivers completely within ice. Debris frozen within the glacier or too large to be transported by meltwater streams can represent a considerable fraction of the total volume of eroded material and will be neglected by estimates considering meltwater sediment loads only. Thus, it is uncertain if the erosion rates cited above are representative of the rate of erosion of past or future continental glaciers.

Geomorphic investigations have provided most of the data used to determine the probable depth of erosion by Pleistocene glaciation, and these data have shown some correlation between interpreted preglacial relief and the amount of glacial erosion (Flint, 1957). However, it is often impossible to ascertain preglacial topography, and misinterpretations may lead to a wide range of perceived depths of erosion. For example, it is generally accepted that erosion was most active at the periphery of continental ice sheets, and erosion of landscapes near glacier centers (such as the Canadian Shield) was minimal (Gravenor, 1975) or less than 10 m (Flint, 1957). In contrast, stratigraphic and geomorphic interpretations of preglacial landscapes by White (1972) indicate that continental glaciers were much more effective agents of erosion than are generally recognized, and that glaciers may have eroded the Canadian Shield to a depth of a few hundred meters. Although few glaciologists agree with these interpretations, it is clear that even the most widely accepted concepts about glacial erosion are subject to disagreement. Only limited confidence should be placed on comparative morphology studies of glacial erosion (Price, 1973).

Flint (1957) cites depths of glacial erosion that have been interpreted in the United States and indicates the importance of topographic control on scouring. In the northwest portion of the United States, covered by the Cordilleran ice sheet during the Pleistocene, topography severely limited glacial erosion. The Coast Ranges and Rocky Mountains experienced deep erosion (up to 315 m into bedrock) in narrow valleys, but they served to shield the Interior Plateau from deep scouring (Richmond, et al., 1965). In the northeast portion of the United States, the presence of steep, narrow valleys parallel to the direction of glacial movement and weak shale bedrock dipping in the direction of ice movement resulted in extremely deep erosion (greater than 600 m) in the Finger Lakes Region (Flint, 1957). Other north-south trending valleys in the Northeast also experienced deep erosion (Connecticut River Valley - 80 m; Susquehanna River near Wilkes Barre, PA - 68 m). Rock basins in the lower Hudson River valley were eroded by glaciers to depths exceeding 200 m below sea level (Price, 1973). The absence of weathered bedrock and residual soil in New England indicates that glaciers probably removed all preglacial soil and weathered bedrock, and the thickness of deposits of glacial drift may be comparable to the thickness of eroded bedrock (Flint, 1957). Jahns (1943) interpreted the depth of erosion in jointed granites in New England to exceed 50 m.

In summary, it has been shown that the large uncertainties involved in measurements of glacial scouring and morphologic interpretation of the depth of glacial erosion combined with the many variables controlling the depth of glacial erosion make prediction of potential depths of scour by future glaciers at specific locations impossible. However, geologic evidence from past glaciations indicates that:

- a. in glaciated areas, the impact of glacial erosion on the landscape exceeded that of fluvial erosion,
- b. glaciers can erode the landscape to well below the base level of fluvial erosion,
- c. glaciers can scour weathered and fractured bedrock to depths exceeding 600 m in terrain favorable to high velocity glacial flow, and
- d. glaciers can abrade fresh, competent bedrock to depths of 40 m or more.

4.5.2 Fluvioglacial Erosion

It is known that glaciation can modify preglacial fluvial systems, but the full extent of these modifications is difficult to interpret. Glaciers can alter surficial drainage patterns by: damming existing valleys and forcing preglacial rivers to erode new valleys, supplying large volumes of meltwater that increase preglacial river volumes or form new rivers, and scouring new paths of drainage by ice action or catastrophic outbursts of meltwater stored within the glacier. Observations of these processes in modern glaciers have been limited to tunneling into ice to study englacial fluvial systems and continued monitoring of the dynamics of active glacier fronts (Price, 1973). Investigators have been unable to predict patterns of drainage derangement by ice damming or outbursts of englacial meltwater in active glaciers (Arnborg, 1955).

Glacial hydrology is poorly understood and only qualitative generalizations about meltwater behavior can be made. The location of meltwater channels within a glacier depends on the glacier's temperature and structural characteristics. Meltwater streams on the surface of glaciers can enter through cracks that extend up to 30 m deep, but the origin of englacial streams known to exist at greater depths is unknown. The direction of englacial meltwater flow cannot be predicted by examining preglacial landscapes. Consequently, the conditions leading to past and present outbursts of englacial rivers are not fully known. Moreover, advance and recession of active ice fronts that can lead to local damming and release of small ice-marginal lakes cannot be predicted. Geologic studies have shown, though, that large proglacial lakes were impounded repeatedly by glacial advances and recessions during the Pleistocene and these lakes might be impounded again during future glaciations (Geotechnical Engineers Inc., 1980).

Although observations of hydrologic processes in modern glaciers have not provided much data on the mechanics of fluvioglacial erosion, impressive geologic evidence of the effects of fluvioglacial erosion on the landscape has been discovered. Stratigraphic studies identifying abandoned river channels have shown that major river systems (for example, the Columbia, Mississippi, Missouri, Ohio and Hudson Rivers) were diverted hundreds of miles

from their preglacial valleys (Flint, 1957; Price, 1973). Erosion features also show that these rivers once flowed with much larger volumes and velocities.

Fluvioglacial channels of erosion have characteristics which distinguish them from typical fluvial channels. They can start and terminate in areas inconsistent with active fluvial development and can dissect modern drainage divides. Fluvioglacial channels usually have steep sides and are remarkably straight and uniform in width for long distances. The channels may be completely dry or contain underfit streams (streams that appear to be too small to have eroded the valley in which they flow) that have relatively few tributaries. The discharge ends of the channels also frequently contain large outwash fans of widely graded sediments. The extent and depth of these channels suggest the extreme erosive power of the extinct fluvioglacial systems and can be attributed to catastrophic floods with tremendous volumes and velocities. Evidence of these floods is found in areas where proglacial lakes were once impounded, and channels incised as deep as 120 m into bedrock have been observed in the channeled scablands of Washington, where glacial Lake Missoula was impounded (Patton and Baker, 1978).

Many fluvioglacial channels cannot be identified morphologically because they have been buried by subsequent glacial deposition. Geophysical methods (such as seismic reflection or refraction) have been used to determine the locations of buried channels.

Studies of assemblages of glacial and fluvioglacial deposits have yielded the following conclusions regarding the location of fluvioglacial channels of erosion (Price, 1973):

- a. No unique correlations have been found between preglacial relief and fluvioglacial channels. Contemporary investigations of active glaciers and morphologic interpretations indicate that the position of meltwater channels relative to a glacier depends on climate, characteristics of the glacier (thickness, temperature, ice regime), local topography, and lithology.
- b. In major valleys trending away from former ice margins, meltwater probably accelerated valley erosion, but difficulty in differentiating between preglacial, glacial, and postglacial components of erosion makes

it impossible to interpret accurately the impact of fluvioglacial processes.

- c. In areas that experienced multiple glaciations and repeated impounding of glacial lakes, it is probable that fluvioglacial channels repeatedly provided outlets for glacial meltwater. Future glaciations may reactivate these channels and encourage further catastrophic erosion.
- d. It is likely that glacial drift has obscured the location of many fluvioglacial channels, and fluvio-glacial erosion may have been more widespread than is currently recognized.

4.6 Wind Erosion

Although wind is a much less effective agent of erosion than rivers or glaciers, it is unique in that it is an active agent that has the capacity to erode below the base level of fluvial erosion and is most effective in arid areas where fluvial erosion is minimal. Wind erosion occurs either by deflation, the process of removing loose sediments, or by abrasion of rock surfaces with wind-transported sand grains. Rock surfaces may be grooved and polished by abrasion, but it is unlikely that grooves or notches can be cut into bedrock more than a few centimeters deep (Bloom, 1978). Thus, abrasion by wind would have no impact on a deep radioactive waste repository.

Deflation has been known to erode basins up to 100 m deep in loose, fine-grained soils susceptible to wind erosion (Longwell, et al., 1969). The potential depth and extent of deflation basins are limited by the location of bedrock, the water table, or vegetative surface cover. Since radioactive waste repositories would be located in competent rock, deflation could not exhume a repository. The greatest potential hazard that deflation could pose for a deep repository in rock would be the erosion of deep basins above a repository that may collect precipitation during pluvials and form lakes supplying groundwater flow through the repository (Bachman, 1874).

5. CONCLUSIONS

Surficial erosion can damage the containment capabilities of a deep radioactive waste repository by exhuming the repository, shortening potential paths of waste migration from the repository to the accessible environment, removing barriers to seepage into the repository, or reducing the volume of rock needed to dissipate thermal energy released from wastes stored in the repository. Surficial deposition will normally improve long-term containment capabilities of a deep repository by increasing the depth of burial beneath ground surface. Only in special cases may rapid surficial deposition activate processes that may be detrimental to repository integrity, such as diapiric movement in salt domes.

It is presently beyond the state-of-the-art to predict the depth of surface erosion that will occur at a given location within a given time period. Measurements of average rates of regional denudation may give no indication of the local rate of erosion that may occur at a repository site within the region. Modern rates of erosion may differ significantly from future rates, depending on tectonic activity or fluctuations in climate and environmental conditions. However, measurements of regional erosion rates may be useful for comparing the relative susceptibility of regions to active erosion. Regions exhibiting the highest rates of erosion are usually characterized by high relief and elevation, sparse vegetative cover, or highly erosive surface lithologies (such as soil or weathered bedrock).

Although future rates of erosion cannot be predicted, the maximum depth of fluvial erosion is limited. The ultimate depth of fluvial erosion is limited by sea level elevation, but temporary base levels located above sea level may prevail for long periods of time in intercontinental regions. Local base levels may be identified morphologically as the elevation of the floodplain of an old-age stream or the elevation of ground surface in an area that has experienced extensive peneplanation and has little or no relief. Detailed geologic investigations of regional morphology and stratigraphy are needed to interpret accurately the stage of landform evolution in such regions and to identify the elevations of local base levels with confidence.

In order to ensure that a repository will not be exhumed by fluvial processes, the repository should be buried beneath the elevation of the base level limiting the depth of erosion in the region containing the repository. The repository should also be sited so that waste migration paths will not be shortened prohibitively by erosion or natural barriers to waste migration will not be penetrated during the required period of waste containment. It has been shown that tectonic activity or climatic variations can affect the eleva-

tion of base level, and these factors must be considered when siting a repository. Geologic evidence indicates that during the Quaternary period in tectonically stable regions, climate fluctuations produced apparent sea levels (which mark the elevation of the ultimate erosion base level) as much as 130 m below present sea level. Thus, to account for potential variations in base levels during future climate fluctuations, repository horizons should be located at least 130 m beneath the elevation of present regional base levels to prevent future exhumation by fluvial processes.

Eolian and glacial processes are not limited by the fluvial erosion base level. Although fluvioglacial erosion is somewhat limited by sea level, the violent release of large volumes of meltwater can produce scouring below sea level. The depth of wind erosion is limited by vegetative cover, the elevation of the groundwater table, or the elevation of unweathered bedrock. Consequently, eolian processes will not seriously constrain the siting of repositories in bedrock. In areas near the margins of Pleistocene englacial lakes locally scoured bedrock to depths exceeding 120 m. Scouring by glacial ice locally eroded bedrock to depths exceeding 600 m. Thus, geologic investigations must be conducted to determine the maximum depth of glacial scouring in glaciated regions that may provide potential sites for repositories. Repositories must then be buried so that equivalent additional scouring will not result in exhumation of the stored radioactive waste.

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A. Before Stream Downcutting

B. After Stream Downcutting

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Livermore, California

Impact of Surficial Erosion and Deposition on a
Radioactive Waste Repository

IMPACT OF EROSION ON
GROUNDWATER RECHARGE
AND DISCHARGE

Φ GEOTECHNICAL ENGINEERS INC
WINCHESTER • MASSACHUSETTS

Project 80654

June 26, 1980 Fig. 1

$$i_{\text{before peneplanation}} = \frac{h_1 + \Delta h - h_2}{s} = i_b$$

$$i_{\text{after peneplanation}} = \frac{h_1 - \Delta h - h_2}{s + \Delta h} = i_a$$

Assuming all head losses occur in aquiclude

Lawrence Livermore Laboratory
Livermore, California

GEOTECHNICAL ENGINEERS INC.
WINCHESTER • MASSACHUSETTS

Impact of Surficial Erosion and Deposition on a
Radioactive Waste Repository

Project 80654

IMPACT OF EROSION ON
ARTESIAN AQUIFER LEAKAGE

June 26, 1980

Fig. 2

FROM SCIENCE APPLICATIONS INC.(1976),p.2-11

Lawrence Livermore Laboratory Livermore, California	Impact of Surficial Erosion and Deposition on a Radioactive Waste Repository	TRANSIENT THERMAL POWER EMITTED BY REPROCESSED LIGHT WATER REACTOR WASTES
GEOTECHNICAL ENGINEERS INC WINCHESTER • MASSACHUSETTS	Project 80654	June 26, 1980 Fig. 4

FROM LANGBEIN AND SCHUMM (1958), p.1077

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Livermore, California

Impact of Surficial Ero-
sion and Deposition on a
Radioactive Waste Reposi-
tory

INFLUENCE OF CLIMATE AND
PRECIPITATION ON STREAM
SEDIMENT YIELD

GEOTECHNICAL ENGINEERS INC.
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Fig. 5

FROM WOLMAN (1967)

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Impact of Surficial Erosion and Deposition on a
Radioactive Waste Repository

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IMPACT OF LAND USE
CHANGES ON STREAM
SEDIMENT YIELD

June 26, 1980

Fig. 6

AFTER RUXTON AND McDOUGAL(1967)

Lawrence Livermore Laboratory
Livermore, California

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Impact of Surficial Ero-
sion and Deposition on a
Radioactive Waste Reposi-
tory

Project 80654

CORRELATIONS BETWEEN AVER-
AGE DENUDATION RATES AND
TOPOGRAPHY

June 26, 1980

Fig. 7

AFTER RUXTON AND McDOUGALL(1967)

Lawrence Livermore Laboratory Livermore, California	Impact of Surficial Erosion and Deposition on a Radioactive Waste Repository	DENUDATION RATE AS A FUNCTION OF ALTITUDE
GEOTECHNICAL ENGINEERS INC WINCHESTER • MASSACHUSETTS	Project 80654	June 26, 1980 Fig. 8

FROM BLOOM (1978), p. 290

Lawrence Livermore Laboratory Livermore, California	Impact of Surficial Erosion and Deposition on a Radioactive Waste Repository	TIME REQUIRED TO LOWER THE HYDROGRAPHERS RANGE, PAPUA, NEW GUINEA
Φ GEOTECHNICAL ENGINEERS INC WINCHESTER • MASSACHUSETTS	Project 80654	June 26, 1980 Fig. 9