

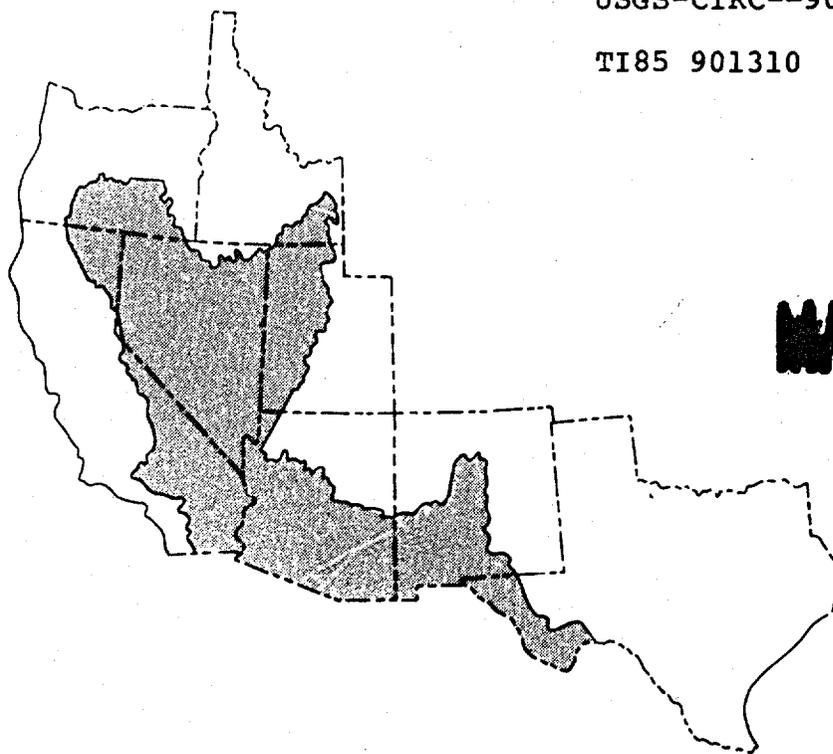
Geologic and Hydrologic Characterization and Evaluation of the Basin and Range Province Relative to the Disposal of High-level Radioactive Waste

Part I Introduction and Guidelines

By M. S. Bedinger, K. A. Sargent and J. E. Reed

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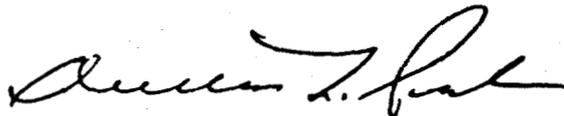
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FOREWORD

The U.S. Geological Survey is actively participating in the national program to identify sites suitable for permanent disposal of high-level radioactive wastes by conducting research and areal studies. This report introduces the U.S. Geological Survey's pilot effort in screening large physiographic provinces of the United States for favorable geohydrologic environments for isolation of high-level radioactive waste. As a part of the national program, the U.S. Geological Survey also provides advice on Earth-science aspects of the program to the States involved and other Federal agencies, including the U.S. Department of Energy, who has the primary responsibility for disposal of high-level waste, as set forth in the Nuclear Waste Policy Act of 1982. Thus the U.S. Geological Survey is using its extensive expertise to help find potentially suitable disposal sites, while maintaining its customary impartiality and scientific objectivity.

The search for repository sites in the United States is almost 2 decades old and has proven to be considerably more complex, both technically and politically, than was originally conceived. Experts within the U.S. Geological Survey believe that past searches for sites placed too much emphasis on candidate host rocks for the repository and too little emphasis on hydrologic setting. Aside from physical exhumation by erosion, meteorite impact, or volcanic activity, ground-water flow is the only natural mechanism by which radionuclides could be transported to the biosphere from an underground repository. Thus, from the initial stages, the present study considered the pathways of ground water that might transport radionuclides from the repository to the accessible environment. Because it was not certain at the outset whether sufficient data would be available to successfully test this approach, the study has served as a pilot effort to determine the feasibility of this approach. The Basin and Range Province has been an ideal setting for the prototype study because of the diversity of its rock types and geologic and hydrologic situations.

A unique feature of this study has been the involvement from the outset, of the States in the Basin and Range Province in the screening process. Technical representatives of the States have provided consultation in choosing criteria, assembling geohydrologic data, and assessing this information to identify environments that meet the criteria for further study. This joint effort does not oblige the States to accept any final choices or priorities resulting from the screening, but it does mean that technical representatives of the States have participated in the screening process from its inception, and that conclusions presented in this and subsequent reports in this series represent a general technical consensus.



Director,
U.S. Geological Survey

PREFACE

This report, part I of a three-part report, provides a background and an introduction to a screening study to evaluate the suitability of environments in the Basin and Range Province for disposal of high-level radioactive waste, and a discussion of guidelines for geologic and hydrologic factors that will be used in the evaluation process. Part II is a reconnaissance-level characterization of the geologic and hydrologic factors to be used in the initial screening of the Basin and Range Province. Part III is the initial evaluation of the Province, using the guidelines established in Part I, and will identify regions that appear favorable for further study.

Parts II and III, as summary reports, will not contain all the detailed information used in characterization and evaluation. The detailed information will be compiled from many published reports, files of the U.S. Geological Survey, and other sources. Some sets of information will be used directly from earlier published reports. The information compiled will be published in separate reports of the U.S. Geological Survey. Following the study of the Province, regions that appear favorable for further study will be characterized in greater detail and further evaluated in a later phase of the study.

M. S. Bedinger

K. A. Sargent

CONTENTS

	Page		Page
Foreword	III	Guidelines for Province evaluation—Continued	
Preface	V	Geologic and hydrologic factors—Continued	
Summary	1	Host rocks—Continued	
Introduction	2	Lateral extent	7
Background	2	Strength, mineability, and thermal	
Origin of the study	3	conductivity	7
Purpose, scope, and methods of study	4	Ground-water flow system	7
Acknowledgments	5	Quaternary tectonic conditions	9
Guidelines for Province evaluation	5	Geomorphic processes and climatic change	10
Geologic and hydrologic factors	5	Flooding	10
Host rocks	6	Natural resources	10
Depth	6	Geohydrologic environments	10
Thickness	6	References cited	15

ILLUSTRATIONS

	Page
FIGURE 1. Map showing physiographic provinces in the conterminous United States	3
2. Graph showing repository nuclide inventories at various years after closure	8
3-6. Sections showing geohydrologic settings in:	
3. Granite and basin-fill deposits in a region of interbasin flow	12
4. Volcanic rocks overlying Paleozoic rocks	13
5. Granitic rocks intruding Paleozoic rocks	14
6. Basin-fill deposits in a large regional flow system	15

TABLE

	Page
TABLE 1. Values of effective porosity, hydraulic conductivity, and retardation factors used to calculate traveltimes	11

CONVERSION FACTORS

Multiply English unit	By conversion factor	To obtain metric unit
square mi (mi ²)	2.590	square kilometer (km ²)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
inch	2.540	millimeter (mm)

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PART I
INTRODUCTION AND GUIDELINES

By M.S. Bedinger, K.A. Sargent, and J.E. Reed

SUMMARY

The U.S. Geological Survey's program for geologic and hydrologic evaluation of physiographic provinces to identify areas potentially suitable for locating repository sites for disposal of high-level nuclear wastes was announced to the Governors of the eight States in the Basin and Range Province on May 5, 1981. Representatives of Arizona, California, Idaho, New Mexico, Nevada, Oregon, Texas, and Utah, were invited to cooperate with the Federal Government in the evaluation process. Each Governor was requested to nominate an Earth scientist to represent the State in a province working group composed of State and U.S. Geological Survey representatives.

This report, Part I of a three-part report, provides the background, introduction and scope of the study. This part also includes a discussion of geologic and hydrologic guidelines that will be used in the evaluation process and illustrates geohydrologic environments and the effect of individual factors in providing multiple natural barriers to radionuclide migration.

Part II is a reconnaissance characterization of the geologic and hydrologic factors to be used in the initial screening of the Basin and Range Province. Part III will be the initial evaluation of the Province and will identify regions that appear suitable for further study.

The plan for study of the Province includes a stepwise screening process by which successively smaller land units are considered in increasing detail. Each step involves characterization of the geology and hydrology and selection of subunits for more intensive characterization. Selection of subunits for further study is by evaluation of geologic and hydrologic conditions following a set of guidelines. By representation on the Province Working Group, the States participate in a consultation and review role in: (1) Establishing geologic and hydrologic guidelines, and (2) characterizing and evaluating the Province. The States also participate in compilation of geologic and hydrologic data used in characterizing the Province.

The current (1983) needs for a high-level radioactive waste repository include: (1) Disposal in a mined repository; (2) re-

trievability of the waste for as much as 50 years; and (3) confidence of isolation of the waste from the accessible environment. Isolation of the waste needs to be assured using geologic and hydrologic conditions that: (1) Minimize risk of inadvertent future intrusions by man; (2) minimize the possibility of disturbance by processes that would expose the waste or increase its mobility; and (3) provide a system of natural barriers to the migration of waste by ground water. The guidelines adopted by the Province Working Group are designed to provide a standard with which these conditions can be compared.

The guidelines can be grouped into four principal categories: (1) Potential host media, (2) ground-water conditions, (3) tectonic conditions, and (4) occurrence of natural resources. Ideally the host medium constitutes the first natural barrier to migration of radionuclides. The host medium ideally should be a rock type that prevents or retards dissolution and transport of radionuclides. Rocks in both the saturated and unsaturated zones may have desirable characteristics for host media. Rocks—other than the host—in the ground-water flow path from the repository ideally should be major barriers to radionuclide migration. Confining beds of low permeability might be present to retard the rate of flow between more permeable beds. Additionally, sorption of radionuclides by materials such as clays and zeolites in the flow path can further retard the flow of radionuclides by several orders of magnitude. Tectonic conditions in an area should not present a probable cause for exhumation or increased mobility of radioactive waste. Natural resources are a factor for consideration because of the problem of future human intrusion and exposure to radioactivity in the quest for minerals, oil, gas, water, and geothermal resources.

The ultimate evaluation of the suitability of a geohydrologic environment for developing a mined repository needs to assess all geologic and hydrologic characteristics and their interaction in providing confidence that a geohydrologic environment will effectively isolate radionuclides from human access. Several hypothetical settings with typical geohydrologic conditions in the Basin and Range Province are used to illustrate the effect of multiple barriers in the isolation of radionuclides.

INTRODUCTION

BACKGROUND

The goal of radioactive-waste isolation in mined repositories is to prevent migration of radionuclides to the accessible environment in unacceptable concentrations. Accessible environment was defined in the draft rule by the U.S. Nuclear Regulatory Commission (1981) to mean "those portions of the environment directly in contact with or readily available for use by human beings." As used here, it includes the Earth's atmosphere, the land surface, surface water, and the oceans; it also includes presently used and potentially useable aquifers containing potable or otherwise useable water and presently mined and potentially mineable natural resources. The present program of the U.S. Department of Energy is committed to pursuing a programmatic strategy that will lead to disposal of existing and future commercially generated radioactive high-level and transuranic wastes in mined repositories in geologic formations (U.S. Department of Energy, 1980).

The search for sites suitable as radioactive-waste repositories has been underway for many years in several countries. Many early studies focused on a specific type of host rock. In the United States, early studies concentrated on salt as the host rock. Subsequently, basalt, tuff, granitic rocks, shale, and metamorphic rocks have been considered as potential host rocks. Although the host medium remains important in planning the engineering design of the repository and in acting as the first natural barrier to radionuclide migration, it is now recognized that the hydrologic, geochemical, and tectonic conditions of the repository and its environment are as important as the host rock.

Early studies of high-level radioactive-waste disposal problems assumed that containment by the enclosing rock mass would be virtually complete. With the application of broader discipline studies, specifically geology and hydrology, to prospective environments for waste disposal, the realization came that total isolation of the waste in the immediate vicinity of the repository cannot be assured (Bredhoeft and others, 1978). Winograd (1977) showed that many of the methods currently used in the Earth sciences are not appropriate for predicting conditions or events during the extremely long time required for waste isolation. Earth processes that are of major concern during

the waste isolation storage time include: (1) Rates of radionuclide transport in the ground-water flow system, which in turn reflect chemical reactions of radionuclides with ground water and Earth materials; (2) climatic changes; and (3) tectonic and associated erosional events. To compensate for the limitations in our knowledge, the current rationale for waste isolation emphasizes the need for a series of independent barriers to waste migrations. Multiplicity of these barriers, both engineered and natural, will, it is hoped, compensate for uncertainties in predicting natural and man-induced conditions and events during the time required for waste isolation.

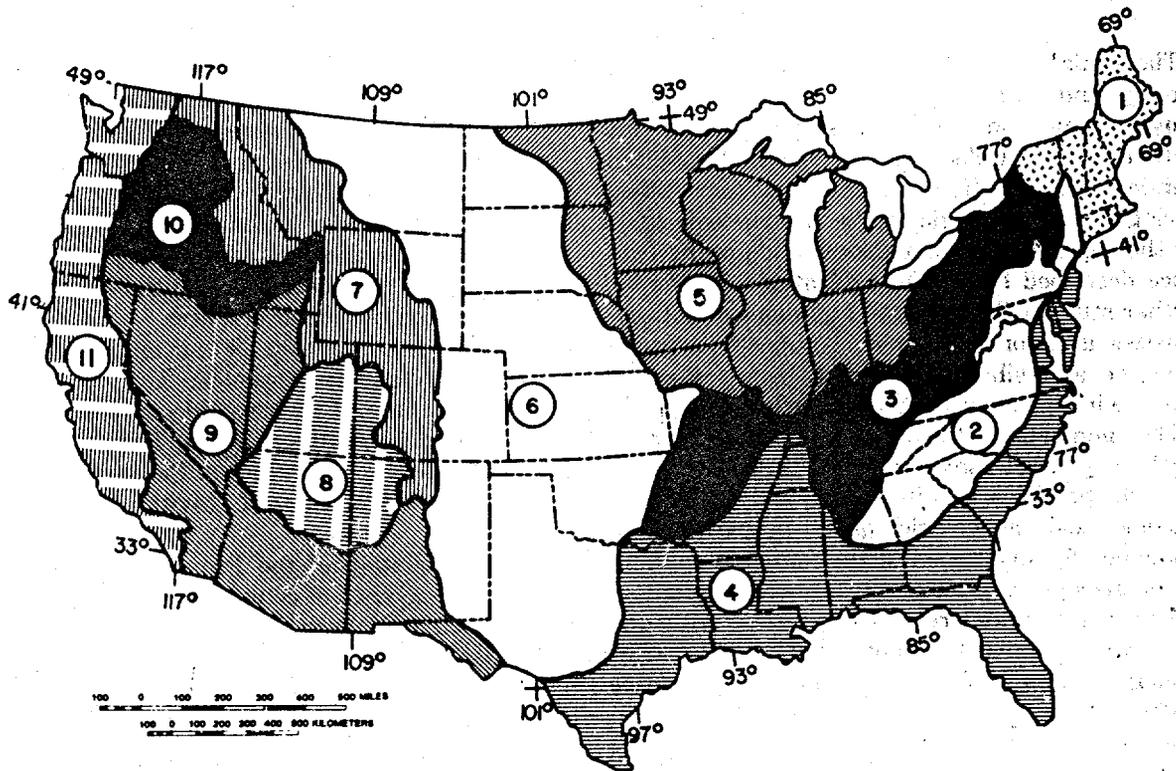
The realization by the Earth-science community that scientific questions and limitations persisted prompted the U.S. Departments of Energy and the Interior to collaborate in assessing the magnitude of the problems. The result of this effort was the "Earth Science Technical Plan for the Disposal of Radioactive Waste in a Mined Repository" (Office of Nuclear Waste Management and U.S. Geological Survey, 1980). The cited report identified technical questions and established five subgroups to address problems in specific areas of concern. Subgroup I, scientists from the U.S. Departments of Energy and the Interior and several States, considered the problem of identification and evaluation of geologic environments potentially suitable for radioactive-waste disposal (U.S. Geological Survey, 1980). The other subgroups were concerned with waste-media interactions, rock mechanics, sealing repositories, and Earth-science aspects of long-term risk analysis.

The approach proposed by Subgroup I was to establish a cooperative State-Federal working group to search for favorable geohydrologic environments containing suitable host media. The search would encompass the conterminous United States by examining the country on a physiographic province basis. The screening plan provided for considering successively smaller land units in each stage and ultimately recommending sites for characterization. Each stage would involve: (1) Characterization of the geology and hydrology; (2) identification of the most favorable subunits; and (3) selection of certain subunits for more intensive characterization. Identification of favorable environments would be based on a set of criteria covering the following: host-rock characteristics, ground-water flow-system characteristics, tectonic conditions, and occurrence of mineral resources.

ORIGIN OF THE STUDY

The U.S. Geological Survey originated the program described herein, referred to as Task I, for Province screening. The study will be guided by, but not constrained to follow the Subgroup I plan. As a prototype, the study of the Basin and Range Province will explore alternative technical methods and strategies for searching for environments favorable for further investigation. Because of the diversity of geohydrologic environments and

the broad base of the U.S. Geological Survey's work in this area, the Basin and Range Province was selected as the prototype in this national screening program (fig. 1). In May, 1981, the U.S. Geological Survey study was introduced to the Governors of the eight Basin and Range States—Arizona, California, Idaho, Nevada, New Mexico, Oregon, Texas, and Utah, and the Indian tribes in those States. The States were invited to participate in the study by designating an Earth scientist to serve on the Province Working Group with U.S. Geological Survey scientists.



EXPLANATION PHYSIOGRAPHIC PROVINCE

1. New England - Adirondack Mountains
2. Appalachian Highlands - Piedmont
3. Appalachian and Interior Plateaus
4. Coastal Plain
5. Glaciated Central Platform
6. Western Central Platform
7. Rocky Mountain System
8. Colorado Plateaus
9. Basin and Range
10. Columbia Plateaus
11. Pacific Mountain System

FIGURE 1.—Physiographic provinces in the conterminous United States.

The membership of the Province Working Group is shown in this report on the inside front cover. The two U.S. Geological Survey members of the Province Working Group are the Project Chief and the Associate Project Chief. The Project Chief serves as Chairman of the Province Working Group. Each State member of the Province Working Group is a scientist designated by the Governor of that State to represent the State on Earth-science questions.

PURPOSE, SCOPE, AND METHODS OF STUDY

The goals of the study are to characterize the geology and hydrology of the Basin and Range Province and identify areas prospective for further, more detailed study in search of potential high-level radioactive waste repository sites. Geologic and hydrologic factors are the sole basis for the characterization and evaluation of the Province described herein. Identification of areas for further study will use a set of guidelines that emphasizes isolation of high-level radioactive waste from the accessible environment by a system of multiple independent natural barriers.

The members of the Province Working Group reach a general agreement on technical issues through participation in study and review of geologic and hydrologic data, preparation of guidelines for evaluation of the potential suitability of geologic environments for waste isolation, and preparation and review of reports. Although the division of work is not inflexible, the U.S. Geological Survey Task I staff members prepare drafts of characterization and evaluation reports. The State members of the Province Working Group provide consultation during report preparation and technical review of the reports. Both the U.S. Geological Survey and State members of the Province Working Group and their respective staffs participate in the compilation, review, and preparation for publication of geologic and hydrologic information used in characterization and evaluation. Participation in this cooperative study does not imply that the States accept the findings and recommendations of this study. The technical interpretations of an individual member of the Province Working Group may differ with the consensus of the group. Any group member may write dissenting opinions for inclusion in reports of the Province Working Group.

Characterization of the Province, Part II of this

report, is based on data and information available in published reports and on unpublished data in the files of Federal agencies, State agencies, universities, and the private sector. The principal factors selected for characterizing the geology and hydrology for the initial screening of the Province consist of:

1. Distribution of selected rocks; including granitic, argillaceous, basaltic, tuffaceous, surface and subsurface evaporitic rocks; and other local occurrences of potentially favorable rock types;
2. regional ground-water flow systems and related data including hydraulic-head relations between principal water-bearing units, depth to water (thickness of the unsaturated zone), water use, natural areas of discharge by evapotranspiration, springs, and water quality;
3. tectonic conditions including the occurrence of Quaternary faults and Quaternary volcanic centers, and the magnitude and historic distribution of seismic activity;
4. metallic and nonmetallic mineral resources, oil, gas, and coal resources; and
5. supplementary Province-wide data and information on geothermal heat flow, uplift and subsidence, occurrence of Pleistocene lakes, and interpretations of gravity and magnetic data.

Initial evaluation of the Province, Part III of this report, consists of comparing the characteristics of each land unit of the Province with the guidelines in the context of a multiple-barrier setting. Negative and positive factors are included to document the evaluation. In many instances, no single criterion is of such overriding importance as to eliminate an environment for further consideration. Lack of technical information, and consequent lack of a basis for evaluation, are documented. The Province evaluation identifies parts of the Province that are prospectively favorable for further study.

Following initial Province evaluation, subdivisions will be selected for additional study and more detailed information will be compiled for the second stage of evaluation. This will include:

1. Stratigraphic sections, including lithologic and other logs of test holes;
2. structural cross sections at selected locations;
3. data on structural processes (folding, faulting), metamorphism, hydrothermal alteration, and other processes that enhance or

detract from the suitability of a rock or area;

4. physical, geochemical, and hydrologic properties of rocks;
5. geochemical environment of the ground-water system in and downgradient from the potential host environments;
6. data on hydrologic conditions and processes such as recharge rates, unsaturated sections, and interbasin flow; and
7. information on surficial geomorphic processes such as potential rates of scarp retreat, denudation, and recurrence of pluvial climates.

ACKNOWLEDGMENTS

This report is the result of a collective effort reflecting the work, assistance, consultation, and experience of many colleagues, both in the U.S. Geological Survey and in State agencies. The plan of this study was guided and influenced by the work of William E. Hale, U.S. Geological Survey (now retired), who was the chairman of Subgroup I of the Earth Science Technical Plan Working Group. The study has been under the administrative and technical guidance of George D. DeBuchanne (now retired), John B. Robertson, and Eugene H. Roseboom, Jr., all of the U.S. Geological Survey. The State members and alternates of the Basin and Range Province Working Group were the principal consultants in the evolution of a plan of work and guidelines that provide a basis for Province screening.

The nucleus of the guidelines for Province screening was drawn largely from a draft of geologic and hydrologic criteria prepared by Newell J. Trask, U.S. Geological Survey, who has continued in a reviewing and advisory role through many drafts of the guidelines. Isaac J. Winograd, U.S. Geological Survey, has contributed to the study from its inception, providing guidance in planning, constructive criticism during its progress, consultation with the Province Working Group on technical problems and critical review of the reports of the Province Working Group. Robert Schneider, U.S. Geological Survey, and John Hawley, New Mexico Bureau of Mines and Mineral Resources, have contributed greatly to the guidelines through review and consultation with the authors.

GUIDELINES FOR PROVINCE EVALUATION

Site criteria developed by several groups—National Research Council of the National Academy of Science, International Atomic Energy Agency, U.S. Department of Energy, and the Office of Waste Isolation—served as a starting point for the Province Working Group in discussions of guidelines. Site criteria of these groups are briefly summarized in a report by the Office of Nuclear Waste Isolation (1981). The recently proposed rule for repository siting of the U.S. Nuclear Regulatory Commission (1981) also affected the design of guidelines used in this report. The guidelines adopted herein for evaluating individual geologic and hydrologic factors are illustrated by the use of hypothetical geologic settings which show the diverse factors that can lead to isolation of waste from the accessible environment and the effect of natural barriers in resisting radionuclide migration.

Guidelines adopted for the Basin and Range Province reflect geologic and hydrologic characteristics of the Province such as aridity, faulting and tectonic extension, the occurrence of areas of high heat flow, areas subject to seismic activity, complex structure, widespread occurrence of a variety of potential host media, large volumes of unsaturated rock, thick non-indurated basin fills, zones with potable and nonpotable ground water, regional bedrock aquifers, and large areas of rock of low permeability.

There follows a discussion of guidelines for geologic and hydrologic factors, such as host rocks, ground-water flow system, and Quaternary tectonic conditions; and then illustrations of how these individual factors are combined in the geohydrologic environment.

GEOLOGIC AND HYDROLOGIC FACTORS

The following discussion of individual factors is based on an arbitrary order, but provides a systematic treatment of the Earth-science factors. Application of the guidelines needs to be made in consideration of the interrelationship of the factors.

HOST ROCKS

The host medium constitutes the first natural barrier to radionuclide migration, excluding engineered barriers of the waste form and the repository. To be most effective as a barrier, host rocks ideally should provide an environment with an absence of free water (that is, zero water velocity) to prevent dissolution and transport of radionuclides. In the Basin and Range Province, these conditions are most nearly attained in unsaturated zones where recharge rates are low or non-existent and moisture contents are minute.

Below the water table, host rocks ideally should retard ground-water movement from the repository and have the capacity to sorb radionuclides. The rate of ground-water movement is slow where rocks have a high effective porosity and a low hydraulic conductivity and where a low hydraulic gradient occurs.

Buffer zones surrounding the repository need not be the same lithologic type as the host rock. However, a homogeneous rock sequence will allow greater confidence in calculations of nuclide transport than an inhomogeneous rock sequence with numerous different lithologic interbeds or zones with significantly different permeability. In general, the greater the thickness of the buffer zone between the repository and any overlying or underlying aquifer, the greater the confidence that the low permeability host rock can contain the waste for long periods.

In the saturated zone, a host rock ideally must have sufficient thickness, lateral extent, and low permeability to provide a medium for waste disposal. In the Basin and Range Province granitic, intermediate and mafic intrusive rocks, argillaceous rocks, ash-flow tuffs, salt and anhydrite, volcanic mudflow (laharic) breccias, basaltic to andesitic rocks, and locally some intrusive rhyolitic plugs and stocks, some partly zeolitized tuff and some metamorphic rock such as granite gneiss, phyllite, and argillite have been inventoried for possible future examination of their host-rock properties.

Many rock types may be potential host media in the unsaturated zone. The suitability of the unsaturated zone is more dependent on the mineability and hydrologic properties of the rocks and their geohydrologic settings than a particular lithology for the rock. In the unsaturated zone, the media ideally should be permeable to provide drainage, have sufficient thickness for repository

construction and buffer zones above and below the repository, and be in an environment with very little or no recharge. Downward infiltration of water through the repository zone would be minimized by a very porous and poorly permeable zone above the repository zone or by very slow recharge rate. Drainage of water which may reach the repository could be facilitated by diversion drains and drainage wells constructed in the repository chambers, and the waste could be further isolated from moisture by engineered capillary barriers (Winograd, 1981).

DEPTH

A deep, mined repository ideally must be located at a depth sufficient to prevent surficial processes from exposing the waste for an extremely long time and to limit the possibility of human intrusion. The depth of the repository ideally should be great enough to preclude a temperature increase at the land surface caused by the heat dissipating from the waste. If the repository is so engineered to impose a maximum temperature of 100° to 150°C in the chamber, model studies show that a repository depth as shallow as 25 meters (82 ft) would cause no more than 2° or 3° C increase in near-surface temperature (D. W. Pollock, U.S. Geological Survey, oral commun., 1983). The minimum depth requirements also need to be analyzed for a given geologic setting with consideration given to such factors as the effects of uplift, downcutting, stream piracy, scarp retreat, and increased rainfall. In some deeply dissected environments, depths of 300 meters (1,000 ft) may be required; while in aggrading subsiding environments, depths of as little as 100 meters (330 ft) may suffice.

There is no generally applicable guideline for maximum depth of a repository. The ambient temperature at the repository depth needs to be considered, because it can affect the heat dissipation and the density of waste emplacement. Considerations determining the maximum depth, such as mining and stability problems, and costs of excavation and construction are beyond the scope of this study. However, 1,000 meters (3,300 ft) is adopted provisionally as the general guideline for maximum depth in screening potential host rocks.

THICKNESS

In the saturated zone, a minimum thickness of 100 meters (330 ft) of host rock would provide a zone for repository excavations with buffer zones

above and below. Below the water table, buffer zones serve as barriers to flow of water to and from the repository.

For disposal above the water table, the thickness of the unsaturated zone ideally must be sufficient to include a buffer zone above the repository, a zone for repository excavations, and a buffer zone between repository and water table. The zone above the repository provides isolation from the land surface and a barrier to exhumation by erosion. The volume of rock between the water table and the repository provides a zone within which the water level may rise relative to the repository without saturating the repository and possible media for delay and sorption of radionuclides before the radionuclides reach the saturated zone. The probable maximum magnitude of water-level rise relative to the repository needs to be examined for each unsaturated environment being considered. The mechanisms by which the water level might rise relative to the repository include climatic changes, which affect the hydrologic system, and tectonic events, which could cause subsidence of the block in which the repository is located. Environments where the depth to water is greater than 150 meters (500 ft) are considered as having potential for further evaluation.

LATERAL EXTENT

The host rock ideally should be continuous over the area of the repository and include a lateral buffer zone. It is estimated that the operations area probably will require a minimum of about 8 square kilometers (3 mi²); the buffer zone probably will extend at least 2 kilometers (1.2 miles) beyond all sides of the operations area.

STRENGTH, MINEABILITY, AND THERMAL CONDUCTIVITY

Because of variability in the physical and engineering properties of rocks, it is not possible to predict these properties at depth with any degree of certainty. However, certain rocks generally are believed to possess undesirable physical properties for mining at depth; for example, certain shales may deform plastically or thin multiple basalt flows may be extensively fractured and subject to caving. Furthermore, certain characteristics observed in surface exposures, such as zones of shearing and other structural complications, and the presence of chemically altered rock, may indicate potential mining problems. Thermal conductivity of the host rock needs to be considered in

the design of the repository to preclude adverse effects to the integrity of the waste form, repository, and host rock as barriers to radionuclide migration. It is generally understood that dense saturated rocks with little porosity, such as salt, dense basalt, and densely welded tuff, have greater thermal conductivities than unconsolidated or extensively fractured media, such as unconsolidated alluvium or brecciated lava flow.

GROUND-WATER FLOW SYSTEM

Major barriers to radionuclide migration ideally should be present in the ground-water flow path from the repository to the accessible environment. A minimum performance requirement of a ground-water flow system specified in revisions to the draft of a proposed rule by the U.S. Nuclear Regulatory Commission (1981) is that the waste be completely contained for 1,000 years following closure and that pre-waste emplacement flow time from the repository to the limit of the controlled area be at least 1,000 years. This time provides for a decrease of several orders of magnitude in the short-lived fission products as shown by the inventory of radionuclides of high-level waste through time (fig. 2), during which strontium-90 and cesium-137 decay to innocuous levels. A flow time of water (or a conservative, non-reactive ion) of 10,000 years from the repository to the accessible environment as defined in this report is adopted as a minimum goal for this study. Sorption of radionuclides by materials in the flow path, or precipitation of radionuclides, particularly for non-oxygenated (reducing) ground water, can further retard rates of movement of some dissolved radionuclides by several orders of magnitude. Rocks composed of clays or zeolitic minerals are notable for their sorptive properties and are effective in retarding transport of radionuclides. In some environments, oxides of iron and manganese appear to be more sorptive for uranium and thorium than are clays and zeolites.

A 10,000-year flow time from the repository to the accessible environment, plus significant sorptive capacity of the flow system will effectively isolate plutonium-239 and americium-243. The longer lived transuranic isotopes, such as uranium-238, neptunium-237, and their daughters in the decay chain, such as radium-226, and long-lived isotopes such as technetium-99 and iodine-129 persist for millions of years—times that are well

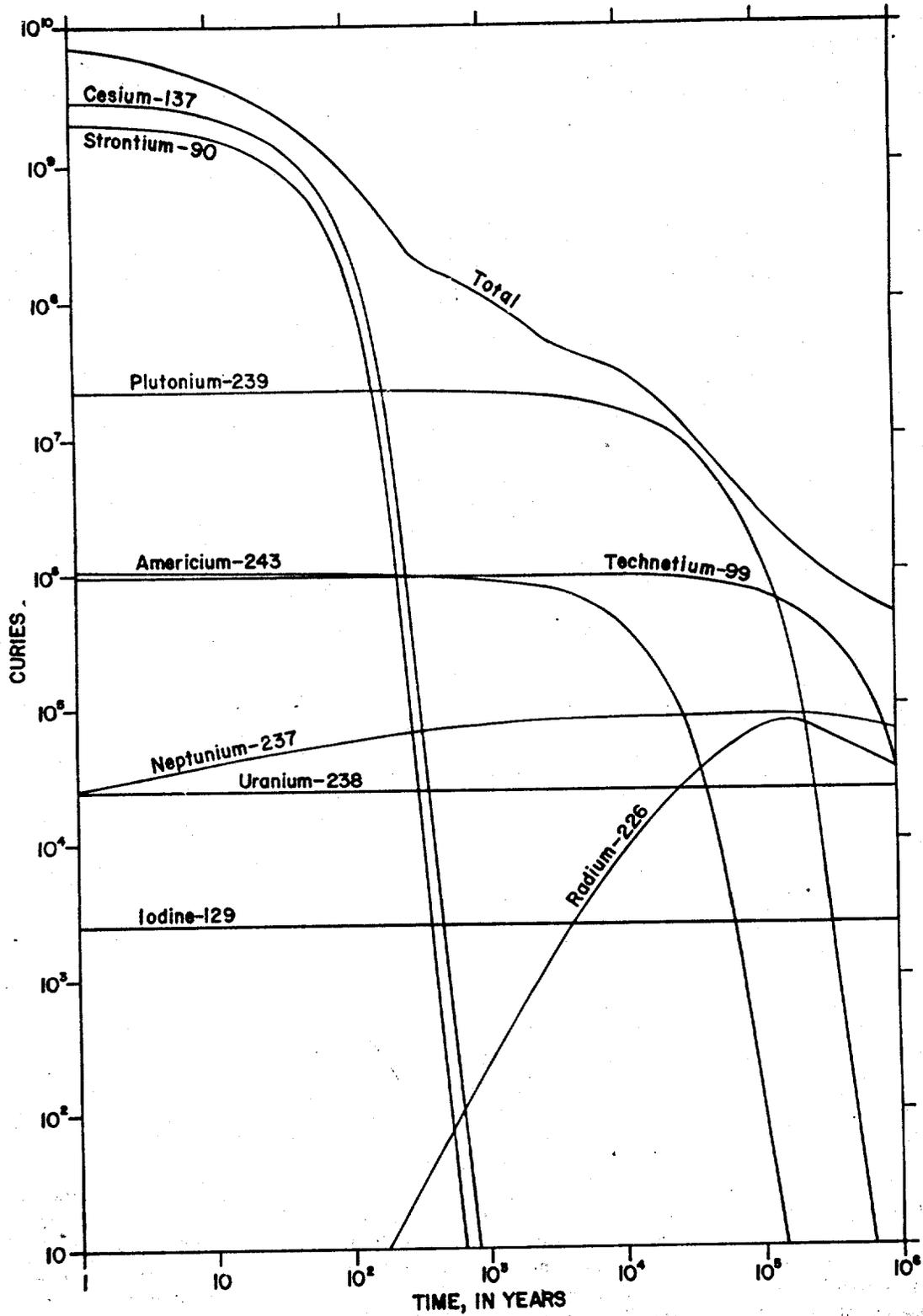


FIGURE 2.—Repository nuclide inventories at various times after closure. Modified from Cloninger and others (1980). The inventory used in the analysis is one-fifth of the total for the spent unprocessed fuel (no-recycle case) estimated to be accumulated in the United States through 2050.

beyond credible predictability for the ground-water flow system.

Decay and sorption of technetium-99 and iodine-129 are not important factors in decreasing their content. Though technetium-99 and iodine-129 content of the waste is reported as a relatively small fraction of the total curie content of the waste by Gera (1975) and Cloninger and others (1980), factors other than sorption will determine the hazard they present. These factors also may be significant in decreasing the hazard of long-lived, sorbed radionuclides. The engineered barrier system of the repository, and the relative insolubility of the waste form and of some of the nuclides will undoubtedly greatly limit their concentration in the water. Significant decreases in radionuclide concentrations can be effected by dilution and dispersion. Dilution occurs where the flow path from a repository enters a large regional aquifer or in some situations, a major stream; dilution can decrease the concentration of a radionuclide by as much as several orders of magnitude. Dispersion occurs in most flow media, occurring to a greater extent in permeable rocks that are extensively fractured and jointed.

For additional information in the radionuclide content of high-level waste, the reader is referred to Gera (1975), American Physical Society (1978), and Cloninger and others (1980); for information on ingestion hazard of high-level waste, the reader is referred to Parker (1981) and Cohen (1982).

Downward or lateral flow of water at the repository horizon would eliminate the risk of upward leakage of radionuclides through poorly sealed shafts or boreholes. However, upward movement through the repository might be acceptable if flow was into an aquifer containing water of non-useable quality and having a long travel-time to the accessible environment.

The possibility of future intrusion of the repository by drilling would be minimized by the following conditions: (1) The potential host rock unit underlain by and immediately overlain by water of non-useable quality; (2) a great depth to a source of useable quality water; or (3) rocks with little water-yielding ability above and below the potential host rock.

QUATERNARY TECTONIC CONDITIONS

Guidelines for tectonic conditions established by other groups generally emphasize tectonic stability (see for example, International Atomic Energy

Agency, 1977, and National Academy of Sciences, 1978) because, under some conditions, tectonic events have the potential for accelerating exhumation of the repository or decreasing the transport time of waste to the accessible environment. In an extreme case, a rupture of the repository by volcanism could transport the waste directly to the accessible environment. The general approach suggested here is to consider the probability of tectonic events in an area as well as to analyze the consequences of tectonic events in a specific geohydrologic environment in a comprehensive, multidiscipline approach. Such an analysis provides a means to ensure that the risks are acceptably small.

The geologic evidence of faults, volcanism, uplift, and tectonic extension during the Quaternary Period (about 2 million years to present) is considered the most useful means to assessing the probability of activity of these factors in the future (U.S. Nuclear Regulatory Commission, 1981). Tectonic activity in the Basin and Range Province is further indicated by historic seismicity and by heat flow.

Seismicity and faulting.—Operational considerations and engineering and construction costs would favor locating a repository away from areas of major seismic activity. However, engineering design can compensate for potential damage to structures by a certain degree of seismic activity. A fault or earthquake near a repository cannot be treated as a "failure" of the system and it need not result in a degradation of the isolation system (Trask, 1982). In some ground-water regimes, such movement may have no effect on the existing ground-water flow system (Davis, 1980). In other ground-water regimes, ruptures may change ground-water flow patterns by creating permeable zones that result in new flow paths.

Most repository-breaching and risk-assessment alternatives considered in the literature (see for example Nuclear Energy Agency, 1980) are for repositories in the zone of saturation. If the repository were in the unsaturated zone, where drainage from the repository is desirable, a rupture near or in the repository after closure might be of minimal significance. A geohydrologic setting in the unsaturated zone in which nearby faulting and associated subsidence and alluviation enhance waste isolation is described by Winograd (1981).

Quaternary volcanism.—Unacceptable risk of volcanic activity at the repository and in the ground-

water flow paths from the repository to the discharge area need to be avoided. A useful example of assessment of volcanic risk was made by Crowe and Carr (1980) for a site in southern Nevada on the basis of studies characterizing the geology, chronology, and tectonic setting of Pliocene and Quaternary volcanism in the region.

Heat flow.—Areas of greater than normal heat flow and the occurrence of thermal springs need to be evaluated for their significance as indicators of relatively shallow igneous activity, upwelling from deep ground-water flow systems, ambient temperatures at repository depth, and with regard to the effects of heat transfer from waste to host rock. Another consideration is that areas with significant heat flow may be subject to subsurface exploration for geothermal energy, thereby providing a potential for human intrusion into the repository area.

GEOMORPHIC PROCESSES AND CLIMATIC CHANGE

Geomorphic processes and climatic changes are important factors where relatively shallow repository environments (150 to 300 meters or 500 to 1,000 ft) are to be evaluated. Geomorphic processes are of concern because of the potential for exhumation of waste by erosion and, conversely, the possible benefit of increased burial depth by aggradation. Factors such as tectonic stability and rates of scarp retreat (Cole and Mayer, 1982), and denudation (Schumm, 1963) or aggradation need to be considered in evaluation of repository environments.

Climatic change is a factor to be considered in evaluating future geomorphic change and in evaluating possible changes in hydrologic conditions that might affect a site. Climatic and associated hydrologic changes extending back to the beginning of the Pleistocene Epoch (about 2 million years before present) will be used as a guide in evaluating future climatic changes. Therefore, the effect of a pluvial climatic cycle (similar to those that occurred during the Pleistocene Epoch) on surface-water and ground-water levels, length of flow paths, and flow times from the repository to the accessible environment need to be considered in evaluating potential repository settings.

FLOODING

Flooding as a factor in repository siting includes the hazard of flooding of the surface-engineering facilities by natural surface runoff and by failure

of man-made or natural impoundments. This factor is site-specific and will not be considered in Province evaluation. Flooding as related to recurrence of pluvial lakes, as existed in the Pleistocene Epoch, was considered in the previous section.

NATURAL RESOURCES

Guidelines discussed heretofore primarily were concerned with natural conditions relating to containment and isolation of high-level radioactive waste. Non-geologic factors are not addressed, as such, in this study. However, the problem of human intrusion in the quest for metallic and non-metallic minerals, hydrocarbon resources, geothermal resources, and water supplies overlaps the areas of geohydrologic and nongeohydrologic factors. Exploration for resources could result in inadvertent human intrusion into the waste repository or into flow paths from the waste (see Cameron, 1981). Society can attempt to prevent intrusion by institutional control of the affected area. Beyond institutional control, documentation of the repository for the benefit of future societies is considered necessary (Kaplan, 1982). Assessments of natural resources need to be made to provide society with the knowledge necessary to make decisions about whether or not to dedicate a volume of earth, and the contained mineral and water resources, to the permanent isolation of waste.

GEOHYDROLOGIC ENVIRONMENTS

Guidelines discussed in the preceding sections consider individual factors as separate entities, yet, they are interrelated. To complement the discussion of individual factors, this section illustrates the interaction of the various factors in the total geohydrologic environment and their effect in providing multiple barriers. The settings are hypothetical, but are similar to combinations of geologic and hydrologic conditions that exist in the Basin and Range Province. For each setting, calculations are made of time of flow from repository to discharge area. The calculations include travel-times through the unsaturated zone, confining beds, and aquifers, and consider retardation of selected radionuclides by sorption. Because these are hypothetical examples, specific aspects are highlighted in each setting. The settings were selected to illustrate favorable flow times from the repository to the discharge area. No attempt is

TABLE 1.—Values of effective porosity, hydraulic conductivity, and retardation factors used in calculating traveltimes.

[Tc, technetium-99; Sr, strontium-90; Am, americium-243; Pu, plutonium-239]

Lithology	Water content	Hydraulic conductivity (meter per year)	Retardation factors			
			Tc	Sr	Am	Pu
Unsaturated zone						
Granite	0.005	1×10^{-2}	1	1	2	10
Zeolitized tuff	.075	6×10^{-4}	1	10	10^2	10^3
Densely-welded tuff	.025	6×10^{-4}	1	2	10	10^2
Sandstone	.005	6×10^{-4}	1	2	10	10^2
Basin-fill sediments	.06	1×10^{-3}	1	2	10	10^2
Saturated zone						
Granite	.01	1	1	1	2	10
Zeolitized tuff	.15	30	1	10	10^2	10^3
Sand, silt, and clay	.3	2×10^3	1	2	10	10^2
Clay and silt	.3	1×10^2	1	10	10^2	10^3
Dolomite	.01	1×10^3	1	1	2	10
Shale	.01	1	1	10	10^2	10^3
Shaley limestone	.01	10	1	2	10	10^2
Quaternary sediments	.3	1×10^3	1	2	10	10^2
Granodiorite	.01	1	1	1	2	10
Sandstone	.01	1×10^3	1	1	2	10
Basin-fill sediments	.3	1×10^3	1	2	10	10^2
Ash-flow tuff	.05	1×10^3	1	1	2	10
Paleozoic carbonate rocks	.01	1×10^3	1	1	2	10

made to systematically discuss and evaluate all other factors in the settings.

Calculations of traveltime and retardation are very conservative; that is, values selected for retardation coefficients are one to two orders of magnitude smaller than values commonly reported as average; values selected for hydraulic conductivity are larger than values commonly reported as average. Consequently, calculated traveltimes of a nonreactive chemical constituent, and radionuclide traveltimes are much shorter than probably exist in the Basin and Range Province. The values of hydrologic and retardation factors used in calculating water-particle and radionuclide traveltime are given in table 1.

Traveltimes estimated in the settings refers to the traveltime of a water molecule or a nonreactive chemical constituent. The following equation relates traveltime of water (t_w) to effective porosity (ϕ), length of flow path (L), hydraulic conductivity (K), and hydraulic gradient (I):

$$t_w = \frac{\phi L}{KI} \quad (1)$$

Retardation refers to the sorption of radionuclides by natural Earth materials in the flow path from repository to discharge area. The radionuclides technetium-99, strontium-90, americium-243, and plutonium-239 were selected to illustrate the retardation effects of sorption radionuclides having half-lives from 29 years to 24,000 years. Calculations of retardation of these radionuclides in the discharge area are based on radionuclide half-life, retardation factors for the radionuclides of the flow-system media, and water-particle traveltime. The retardation factor (K_r) is the ratio of water velocity to nuclide velocity (Cloninger and others, 1980):

$$K_r = 1 + r K_d \quad (2)$$

where r is the ratio of bulk-rock density to effective porosity, and K_d is the ion-exchange distribution coefficient as defined by:

$$K_d = \frac{\text{quantity of nuclide in solid phase/mass of solid}}{\text{quantity of nuclide in liquid phase/volume of liquid}}$$

The traveltime of the radionuclide (t_n) is the product of the traveltime of the water and the retardation factor, or:

$$t_n = t_w k_f \quad (3)$$

In the settings described below, the short- to intermediate-duration (half-life less than 25,000 years), sorbed radionuclides strontium-90, americium-243, and plutonium-239 decay to very small or insignificant concentrations before reaching the discharge area. Technetium-99, which is not sorbed and with a very long half-life does not decrease significantly in the settings.

The geohydrologic environment shown in figure 3 includes a granite cropping out in a range block and extending underneath zeolitized-bedded tuff and clastic basin fill. The hydraulic gradient is 2×10^{-2} (about 30 meters per kilometer or 100 ft/mi) in the granite outcrop area, and 1×10^{-4} (about 2 meters per kilometer or 5 ft/mi) in the basin fill.

Ground water in the playa area is nonpotable; granite characteristically yields little water to wells or excavations. Assuming conservative values of permeability for materials in the flow path, the time of travel from repository A, in the saturated zone in the granite, to the discharge area would be about 30,000 years. Sorption of strontium-90, americium-243, and plutonium-239 by minerals in the flow path, principally in the zeolitized tuff and clay may effect a traveltime for these radionuclides of one to three orders of magnitude greater than water-particle traveltime. For repository B, in the unsaturated zone in the granite, assuming a recharge rate of 1 millimeter per year (less than 0.4 in./yr) or less, leach rate of the waste would be a very small fraction of the rate under saturated conditions, whereas traveltimes would be practically the same as from repository A.

Evaluation of repositories in this and other settings would involve consideration of such factors as: (1) Possibility of exhumation of the repository by slope retreat and denudation, (2) effects of a change in length of flow path and a rise in ground-water level on hydraulic gradient, and consequently on traveltime, (3) seismic hazard of the site, (4) possibility of human intrusion into the repository and into the flow path from the repository in search of mineral resources and water supplies, and (5) possibility of disruption of the repository or the ground-water flow path by faulting or a

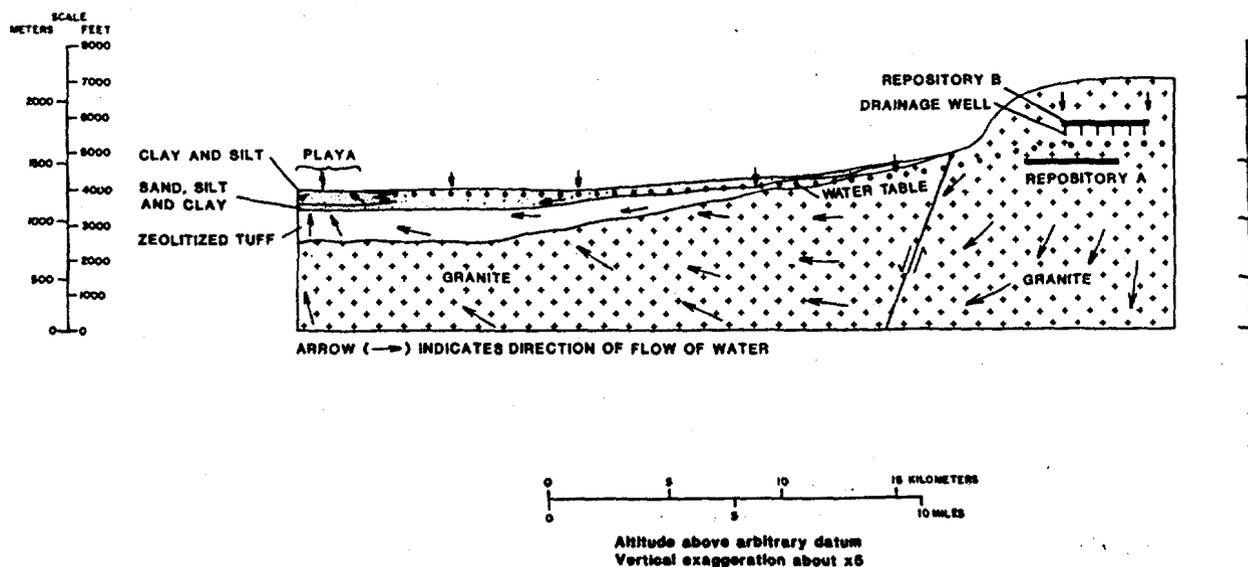


FIGURE 3.—Section showing geohydrologic setting in granite and basin-fill deposits in a region of interbasin flow.

volcanic eruption. The retreat from the fault scarp indicates that the main fault displacement is not recent. However, the trace of the fault needs to be investigated for recent movement.

A setting in a mesa overlying a folded and faulted sequence of carbonates, shales, and sandstones of Paleozoic age is shown in figure 4. Depth to water is about 700 meters (2,300 ft) below the surface of the mesa. A repository in the unsaturated zone could be in a fractured or jointed basalt or densely welded tuff, or in a well-sorted sand that would provide drainage from the repository if recharge from the surface reached the repository. Drainage could be enhanced, if necessary, by wells constructed to drain the repository. Isolation of the waste from contact with the water could be further aided by capillary barriers (Winograd, 1981) constructed around the waste package.

In an arid environment, in which precipitation is greatly exceeded by potential evapotranspiration, recharge rates can be expected to be extremely slow or nil. Leaching of the waste package, if it occurs, would presumably be at a

significantly slower rate than in the saturated zone. However, assuming leaching of the waste occurs, a regional flow system in the Paleozoic rocks, discharging 75 kilometers (47 mi) away from the mesa under an average gradient of 6×10^{-4} , would provide a conservatively estimated traveltime in the saturated zone of about 20,000 years from mesa to discharge area. Transport time of sorbed radionuclides will be one to three orders of magnitude greater because of sorption by zeolitized tuff, clayey siltstone, or a lacustrine sequence that might overlie the Paleozoic rocks. Dilution of the radionuclide concentration would be effected by the greater flow volume and dispersion in Paleozoic rocks. As in the previous example, attendant risks of releasing unacceptable concentrations of radionuclides by tectonic hazards, climatic change, and human intrusion need to be considered.

A setting in which granite has intruded a folded and thrust-faulted sequence of Paleozoic shale, sandstone, limestone, siltstone, and gypsum is shown in figure 5. The hydraulic gradient is 4×10^{-3} for the 29 kilometers (18 mi) from the granite

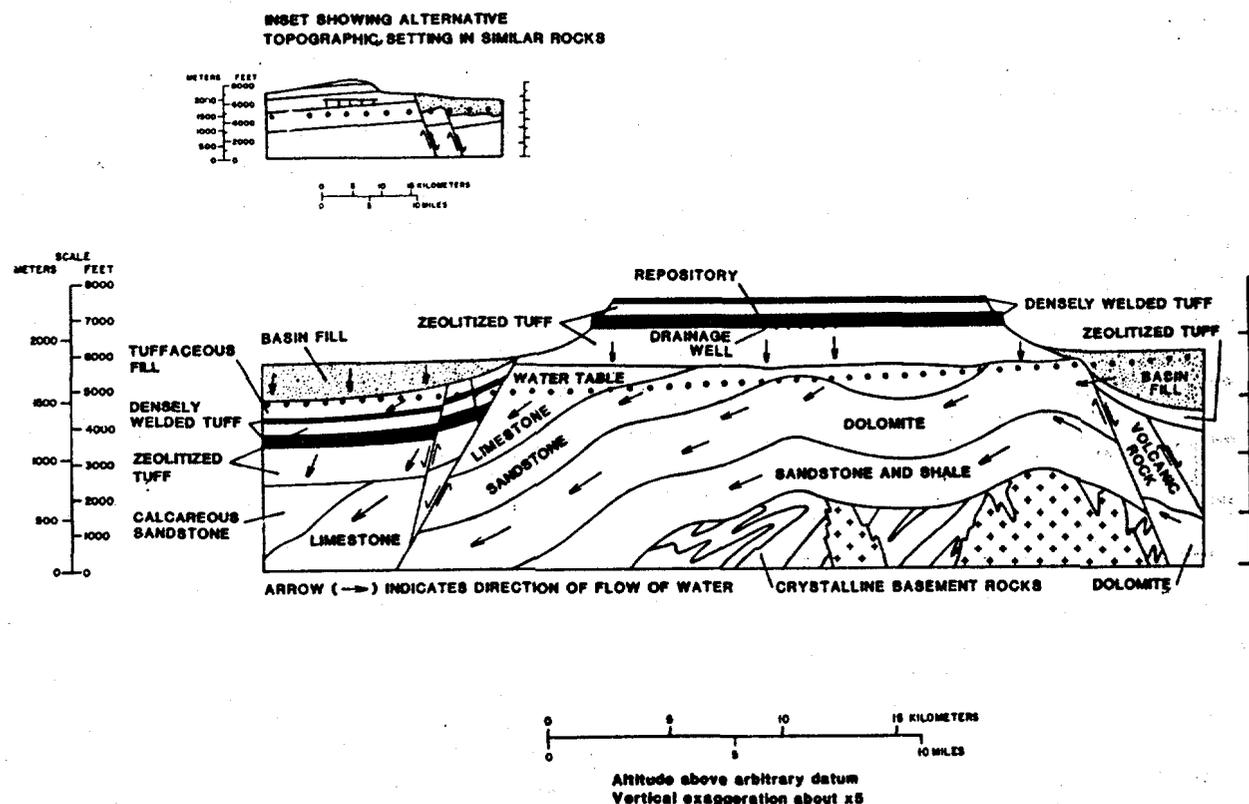


FIGURE 4.—Section showing geohydrologic setting in volcanic rocks overlying Paleozoic rocks.

outcrop to the playa where discharge occurs. Water in the system is not potable because of excessive concentration of dissolved sulfate derived from the gypsum. The traveltime of a water particle from repository A in the shale, or repository B in the granite to the playa would be about 10,000 or 16,000 years respectively. Traveltime of strontium-90, americium-243, and plutonium-239 will be one to three orders of magnitude greater than water-particle traveltime because of sorption in shale beds along the flow path. Thrust faults that cross the ground-water flow path may be ground-water conduits or ground-water barriers. If the faults have significant permeability, the hydraulic gradient will cause water to move downward along the fault planes. If the faults have little permeability, these faults will impede movement of water to the discharge area.

As in the previous examples, the factors of climatic change, tectonic activity, and human intrusion need to be considered. Human intrusion resulting from a search for water supplies is greatly mitigated by the nonpotable quality of the water. The suitability of the shale as a host rock and the feasibility of constructing a mine in the shale is questionable; tests would be needed to determine its homogeneity, permeability, thermal conductivity, chemical properties, lithologic continuity and mining properties.

A setting with repositories in unsaturated basin fill (A) and zeolitized tuff (B) is shown in figure

6. Repository A is at a depth of 150 meters (500 ft) below land surface and about 300 meters (1,000 ft) above the water table. The region is actively undergoing tectonic extension and the basin is aggrading. Seismic activity is greater than normal, and there is a Quaternary fault within 1.6 kilometers (1 mi) of the repository. Paleozoic rocks including a regional carbonate aquifer underlie the basin fill. Distance from the repository to the discharge area of the carbonate-rock aquifer is 65 kilometers (40 mi), and the gradient is 6×10^{-4} . In the arid climate, the recharge rate is very slow to nonexistent. If recharge occurs and the waste were leached, a conservative estimate of traveltime of a water particle to the discharge area would be about 15,000 years. Time of travel of strontium-90, americium-243, and plutonium-239 is one to three orders of magnitude greater than water-particle traveltime, because of sorption in the zeolitized tuff underlying the repository. Also, radionuclide concentrations would be decreased significantly because of dilution and dispersion in the carbonate-rock aquifer.

The great depth to water and the absence of economically mineable resources greatly decrease the possibility of human intrusion. Seismic activity at the repositories is a concern; however, engineering design of site facilities could mitigate the operational problems. Following decommissioning, a breach of the repositories by faulting would not be unacceptable because it would not significantly

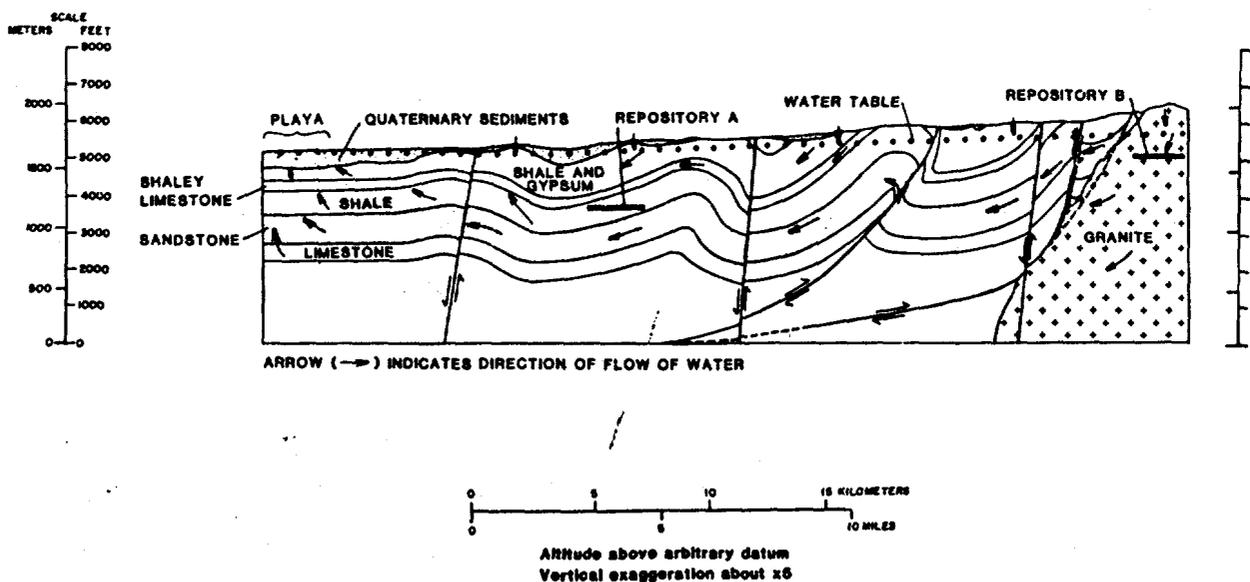


FIGURE 5.—Section showing geohydrologic setting in granitic rocks intruding Paleozoic rocks.

affect radionuclide traveltime to the discharge area. The repositories are located in fault blocks that will subside during active movement along the fault planes. The buffer zones of 200 to 300 meters (660 to 1,000 ft) will adequately protect the repositories from ground-water saturation due to possible rise in water level during a pluvial cycle and subsidence of the basin block. In a similar geohydrologic setting, based on altitude of spring orifices, length of flow path, and transmissivity of the aquifer, and liberal estimates of recharge during the Pleistocene, Winograd and Doty (1980) estimated that the rise of water level in future pluvials would not likely exceed 30 meters (100 ft). Based on rates of movement on faults in the Basin and Range Province given by Trask (1982), subsidence during 1 million years probably would not exceed 100 meters (330 ft).

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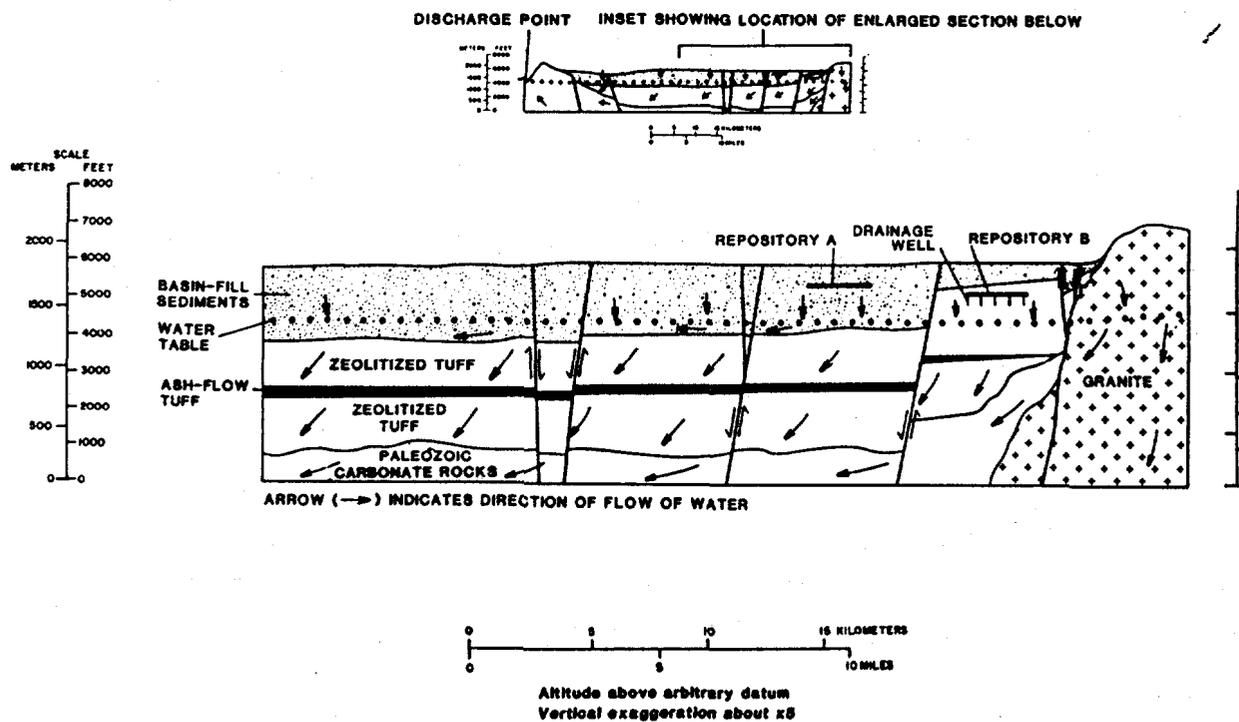


FIGURE 6.—Section showing geohydrologic setting in basin-fill deposits in a large regional flow system.

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