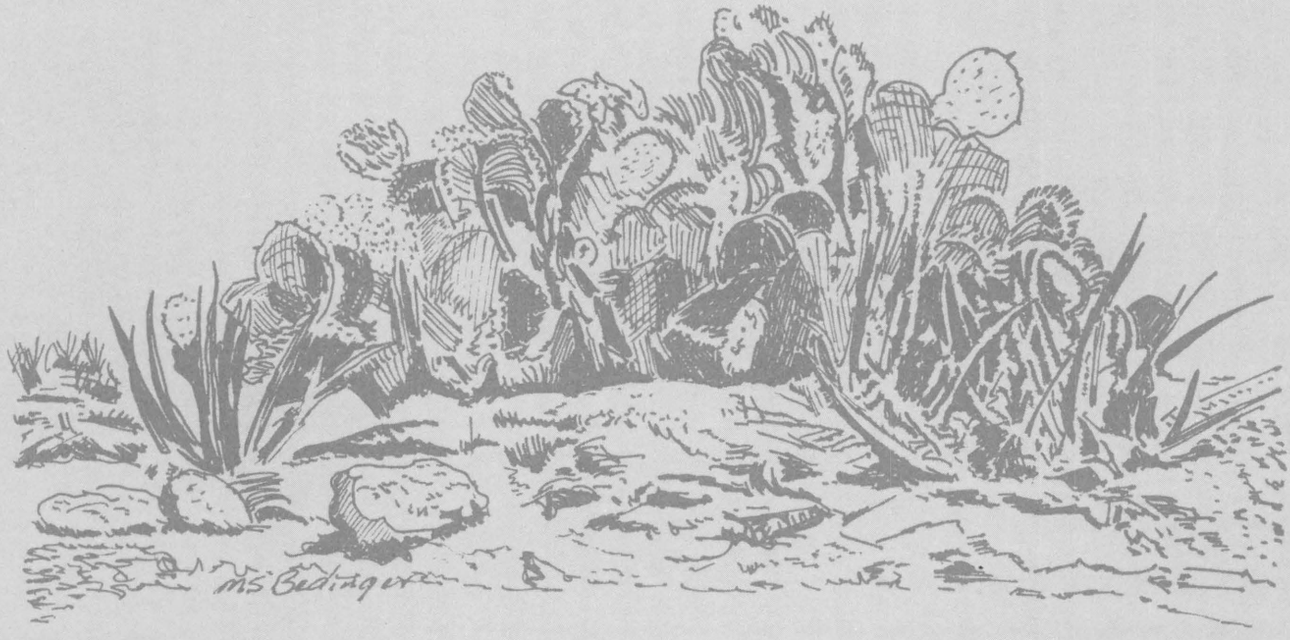
Studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, For Isolation of High-Level Radioactive Waste—Evaluation of the Regions

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1370–H

Prepared in consultation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah



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By M.S. BEDINGER, K.A. SARGENT, *and* WILLIAM H. LANGER

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ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE

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[Plates are in pocket]

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CONVERSION FACTORS

For readers who wish to convert measurements from the metric system of units to the inch-pound system of units, the conversion factors are listed below.

Multiply SI unit	*By*	*To obtain U.S. customary unit*
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow	
meter per minute (m/d)	3.281	foot per day (ft/d)
	Chemical concentration	
milligram per liter (mg/L)	About 1	part per million (ppm)

STUDIES OF GEOLOGY AND HYDROLOGY IN THE BASIN AND RANGE PROVINCE, SOUTHWESTERN UNITED STATES, FOR ISOLATION OF HIGH-LEVEL RADIOACTIVE WASTE—EVALUATION OF THE REGIONS

By M.S. BEDINGER, K.A. SARGENT, and WILLIAM H. LANGER

ABSTRACT

Six regions in the Basin and Range province, ranging in size from 21,600 to 80,000 square kilometers, were evaluated to identify prospective hydrogeologic environments for isolation of high-level radioactive waste. Prospective hydrogeologic environments were evaluated on the basis of the surface distribution of potential host rocks, late Cenozoic tectonic activity, hydrogeologic characteristics, and mineral and energy resources. These regions were selected as prospective for this study from a screening of the Basin and Range province.

The six regions have certain characteristics that appear favorable for isolation of radioactive waste. The scant precipitation and great potential for water loss by evaporation and transpiration results in little surface runoff and ground-water recharge. This, combined with other hydrogeologic factors, results in areas within the regions that have thick unsaturated zones and long ground-water flow paths and traveltimes.

Potential host media in the unsaturated zone include crystalline rocks, volcanic rocks, and basin fill. Potential host media in the saturated zone are predominantly crystalline igneous rocks but also include argillaceous rocks, evaporitic rocks, intracaldera tuffs, and laharic breccias.

Travel times from potential host rock to natural discharge areas are estimated on the basis of estimated hydraulic properties and gradient through the more permeable rock units at depth in the flow system. Traveltimes in many flow systems are projected to be extremely long (more than 10^6 years); much greater than can be predicted with accuracy. Accordingly, a projected traveltime of greater than 100,000 years is considered a conservatively long time. Traveltime through a distance of 10 kilometers in crystalline igneous rocks commonly is projected to be greater than 100,000 years; traveltime through the same distance in carbonate-rock aquifers commonly is projected to be less than 100,000 years.

The Basin and Range province has a history of active tectonism throughout geologic time, with Late Cenozoic tectonic activity in the regions studied generally being less than many areas in the Basin and Range province. Although there are some areas of great tectonic activity in the regions studied, the hazard of future tectonic activity in an area could be minimized by selection based on the absence of Quaternary and historical activity.

Recurrence of the pluvial conditions that existed during the Pleistocene may cause changes in ground-water conditions. These changes may include an increase in recharge, a rise in ground-water levels, and an increase in hydraulic gradients and velocities.

Ground water in the province generally is suitable for most uses, with notable exceptions in some playa areas and in some areas where ground water contains large concentrations of dissolved solids. Ground-water supplies are limited in much of the province.

The regions have mineral potential, but at the present time, mineral and energy resources are not widely developed. Additional assessments of mineral potential need to be made in areas selected for further study.

Potential host media for isolation of high-level radioactive waste in the Trans-Pecos region, Texas, include unsaturated and saturated igneous intrusive rocks and thick sections of tuff and basalt. Igneous intrusions in thick shales hold prospects for hydraulic and geochemical barriers to radionuclide migration. Unsaturated rather than saturated volcanic rocks are considered more favorable as a repository media. The more clearly defined issues of concern are the widespread availability of fresh ground water and the possibility of exploration for mineral and energy resources.

The principal potential host rocks in the Rio Grande region, New Mexico and Texas, are unsaturated and saturated intrusive igneous masses located near the origin of long ground-water flow systems. Natural barriers are provided by fine-grained clastic and crystalline rocks and evaporitic rocks. Saline water and the fine-grained nature of much of the basin fill will limit ground-water development.

Waste-isolation environments in the Sonoran regions of Arizona and California are enhanced by the arid climate with scant precipitation and great potential evaporation, the tectonic stability of the regions, and the long ground-water traveltimes from potential host rocks to natural discharge areas. The potential host media include unsaturated and saturated intrusive rocks and unsaturated volcanic rocks and basin fill.

Manuscript approved for publication, March 1, 1985.

Chemical retardation of radionuclide transport may be afforded by clay minerals in weathered igneous and metamorphic rock and in zeolitic and argillaceous basin-fill deposits.

Potential host media in the Death Valley region, Nevada and California, include tuff and crystalline intrusive rocks in the saturated and unsaturated zones and basalt, tuff, and basin fill in the unsaturated zone. Ground-water traveltime and retardation of radionuclides by sorption probably will afford long-term isolation from the near-surface environment. Tectonic activity is of concern, especially in the western part of the region. Additional studies in this area would be necessary to assess thoroughly hazards posed by tectonic conditions. Ground-water quality in the region is suitable for most uses except in a few terminal discharge areas.

Environments containing unsaturated and saturated intrusive and tuffaceous igneous rocks are potential host media in the Bonneville region, Utah and Nevada. Low permeability and radionuclide retardation by the host rocks would provide the principal barriers to radionuclide migration. The region is relatively quiet tectonically. Water-supply potential is known in the upper part of the basin fill, and the water is suitable for most uses throughout most of the region.

INTRODUCTION

OBJECTIVE OF THIS REPORT

The guidelines for evaluation of the regions, the rationale for their study, and the basis for hydrogeologic characterization of the regions are given in Chapter A. The regions selected for the present phase of study have been characterized in the preceding six chapters (Professional Papers 1370–B through G) of this report series (fig. 1). The information pertinent to identifying environments favorable for the isolation of high-level waste is summarized in these chapters. The objective of Chapter H is to evaluate the geologic and hydrologic conditions in the regions with respect to the guidelines in order to identify areas favorable for further study for isolation of high-level radioactive wastes. Comparisons of favorability of areas between regions are not made. Such comparisons would be of doubtful validity because the information bases from which comparisons would be made are not equal. The titles of chapters in Professional Paper 1370 are as follows:

- **A** Basis of characterization and evaluation
- **B** Characterization of the Trans-Pecos region, Texas
- **C** Characterization of the Rio Grande region, New Mexico and Texas
- **D** Characterization of the Sonoran region, Arizona
- **E** Characterization of the Sonoran region, California
- **F** Characterization of the Death Valley region, Nevada and California
- **G** Characterization of the Bonneville region, Utah and Nevada
- **H** Evaluation of the regions

The reports in this series are closely integrated and contain a minimum of repetition. The reader needs to consult chapters A and H and the appropriate regional chapters B through G in order to achieve a complete understanding of the characterization and evaluation of an individual region.

OVERVIEW OF REGIONAL EVALUATION

The arid to semiarid climate in the Basin and Range province is considered a favorable characteristic for the isolation of high-level radioactive waste. The excess of potential evaporation compared to precipitation and consequent slow rate of recharge throughout much of the region in combination with other geologic and hydrologic factors contributes to areas with very thick unsaturated zones, which are prospective environments for waste isolation. Potential host media in the unsaturated zone include crystalline rocks, volcanic rocks, and basin fill. The estimated ground-water traveltimes from potential host rocks to discharge areas are used as one type of indicator of the effectiveness of an environment in isolating high-level radioactive waste from the human environment. The velocity of water movement in the unsaturated zone is a function of the moisture content, the hydraulic conductivity, and the rate of flux. Velocity of flow above the water table in dense, but fractured, rocks may be relatively rapid and therefore may not add greatly to the traveltime. However, in an arid environment with negligible or no flux in the unsaturated zone, contact of water with the waste will be slight and may be virtually eliminated through the use of engineered barriers. Interstitial flow in unsaturated friable or pumiceous tuff that has a large unsaturated moisture content may contribute significantly to long traveltimes. Problems in identifying and establishing the rate of flow in the unsaturated zone persist because of problems in characterizing the physical processes and nature of the media.

Potential host media in the saturated zone are predominantly crystalline igneous rocks. Other rock types inventoried and considered include evaporitic rocks, laharic breccias, intracaldera tuffs, and argillaceous rocks. With some possible exceptions of bedded salt deposits in the Sonoran region of Arizona, evaporitic rocks are of limited distribution and are inhomogeneous with clastic interbeds. Such characteristics are not considered favorable for host rocks. Laharic breccias locally are extensive. These mixtures of clastic mudflows and volcanic rocks have little permeability and may deserve further evaluation as potential host rocks. In this report, however, they are regarded as low permeability barriers to ground-water flow and as probable retardants to radionuclide transport. Intra-

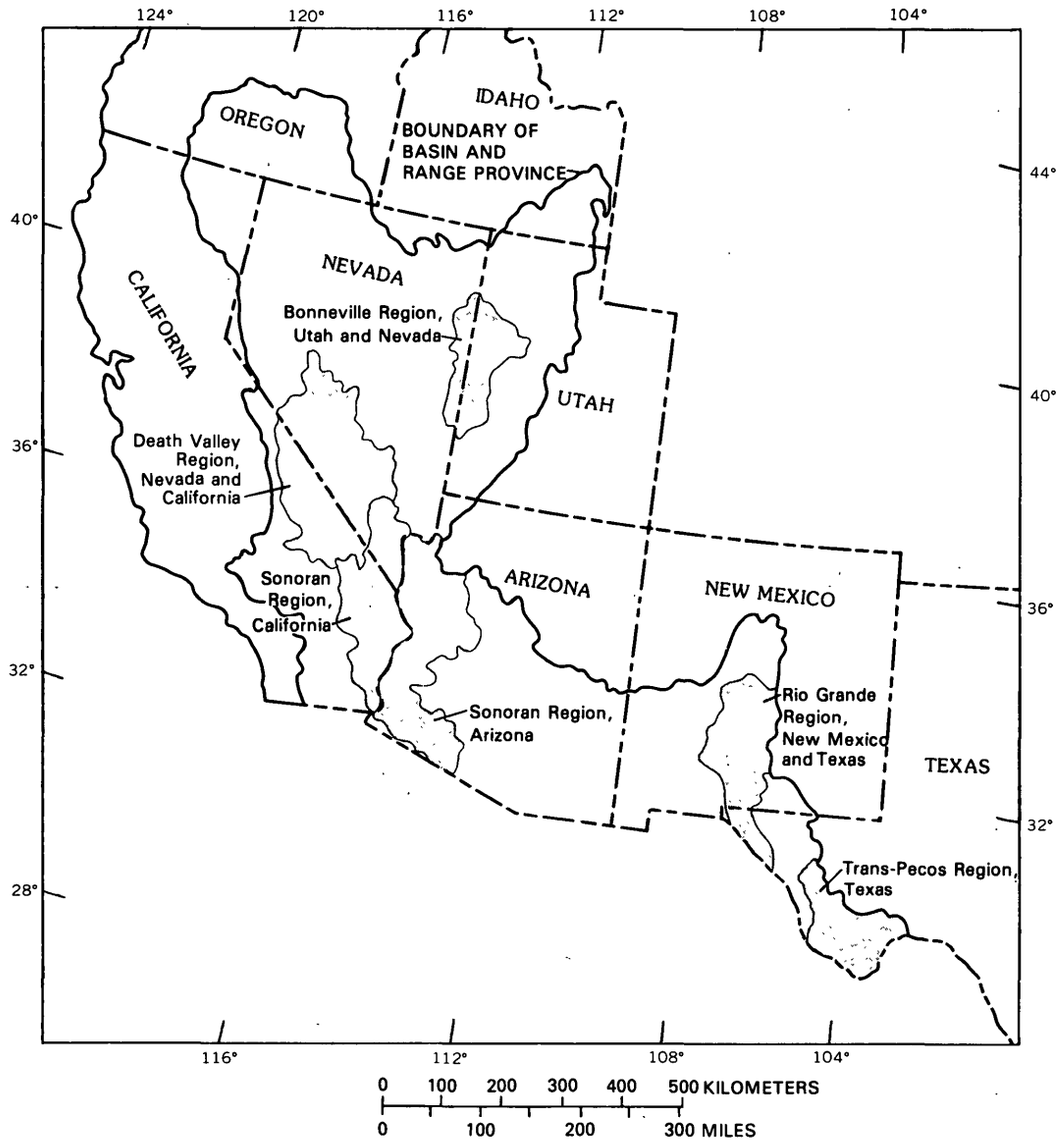

FIGURE 1.—Map of regions of study in the Basin and Range province.

caldera, and locally a few extra caldera, ash-flow tuffs may attain thicknesses as great as 3,000 m. These rocks have small values of interstitial hydraulic conductivity and may have few joints and fractures—favorable properties for a potential host rock in the saturated zone. Argillaceous rocks historically have been considered as potential host rocks. In the western part of the Basin and Range province, the argillaceous rocks are tectonically deformed and of variable character and distribution that not only decreases their desirability as potential host rocks but also decreases their efficacy as ground-water flow barriers. Argillaceous rocks in the Rio Grande and Trans-Pecos regions, though locally faulted, are largely near original attitudes and in continuous layers, some of great thickness. Their lithology and thickness locally may be suitable for consideration as potential host rocks, but their principal advantage to waste isolation is considered to be as barriers to ground-water flow and as geochemical retardants to radionuclide transport.

Relative ground-water velocities and traveltimes in potential host rocks and from potential host rocks to discharge areas are estimated from general properties of the rock types (Chapter A) and from available data on the hydraulic gradient. The estimates of relative ground-water velocity and traveltime are based on ranges of hydraulic properties of the rocks and on limited geologic

and hydrologic knowledge of the regions. The ranges of estimated relative traveltimes are believed to bracket most situations, but unknown hydraulic properties outside the range could cause the estimates to be off by several orders of magnitude. Traveltime through a 10-km distance in crystalline igneous rocks of average permeability and porosity will afford isolation of more than 10,000 yr, and locally much more, except where anomalously fractured. Because of the difficulty of characterizing fracture distribution, permeability, and continuity in crystalline rock, these rocks are considered more favorable as waste-isolation environments where low permeability sedimentary rocks enclose or overlie the igneous mass.

The prevailing lack of detailed subsurface information on the character of the geologic units, their stratigraphic and structural relationships, and hydrologic properties of the rocks and the flow systems, limits analyses that can be made without additional data. Discussions of hydrogeologic environments in the regions are hereby prefaced with the qualification that additional studies are needed to obtain site-specific data from which evaluation of the environments can be made with confidence.

The Basin and Range province has a history of active tectonism throughout geologic time. Late Cenozoic tectonic activity in the regions studied generally is less than in many areas in the Basin and Range province; however, within the regions studied there are some areas of great tectonic activity. The hazard of future tectonic activity in an area could be minimized by selection based on the absence of Quaternary and historical activity. Additional studies of Quaternary and historical tectonism, including seismic activity, Quaternary faults, and all neotectonic activity, need to be made in areas selected for further investigation.

Consideration of the recurrence of the pluvial conditions that existed during the Pleistocene is necessary in a thorough analysis of a potential repository. Changes in ground water accompanying pluvial conditions may include an increase in recharge, a rise in ground-water levels, and an increase in hydraulic gradients and velocities.

Ground water in the province generally is suitable for most uses. However, notable exceptions exist in some playa areas and in some areas where ground water is a calcium sulfate type and contains large concentrations of dissolved solids. Ground-water supplies are limited in much of the province because of the generally low permeability of the bedrock and of the lower part of the basin fill.

Mineral and energy resources have not been widely developed in the regions under study, but the regions have mineral potential. Additional assessments of mineral potential need to made in areas selected for further study.

PARTICIPATION OF THE PROVINCE WORKING GROUP

This evaluation chapter was written by the U.S. Geological Survey Province Working Group members and U.S. Geological Survey staff. The State members of the Province Working Group have had review, consulting, and advisory roles during the screening phases of the project. State members of the Province Working Group have reviewed the technical content of this evaluation chapter for accuracy and consistency. Although the report meets in a general way their concepts of technical accuracy, the State members of the Province Working Group do not necessarily accept in detail all conclusions of this report.

ACKNOWLEDGMENTS

This report and the other reports in this series were prepared in cooperation with the States of Arizona, California, Idaho, Nevada, New Mexico, Texas, and Utah. Each of these States was represented by members of the Basin and Range Province Working Group. The cooperating agencies in each State and members and alternates of the Province Working Group are listed following the title page. The following individuals provided continued advice and assistance to the Basin and Range Province Working Group and in overall planning and execution of the work in preparation of this series of reports: John W. Hawley and William J. Stone of the New Mexico Bureau of Mines and Mineral Resources; Robert B. Scarborough of the Arizona Bureau of Geology and Mineral Technology; T.L.T. Grose of the Nevada Bureau of Mines and Geology and the Colorado School of Mines; and George Dinwiddie and George I. Smith of the U.S. Geological Survey. The authors acknowledge the many perceptive and helpful comments used in the preparation of this report by Isaac J. Winograd of the U.S. Geological Survey.

EVALUATION OF THE REGIONS

Each region of study is discussed separately in this report. The information in the characterization chapters (B through G) of this report series is briefly summarized in an accompanying table for each region. References to the sources of information are not given in this report but can be found in Chapter A and the appropriate chapter

on each region. The guidelines for evaluation and basic source references also are given in Chapter A, as are sections that present the information base for evaluation.

A second table in the section of this report for each region summarizes potentially favorable factors and issues of concern relative to characteristics of the region for potential containment and isolation of high-level radioactive waste.

Each region was selected in the province phase of screening as having potential for further study. Hydrogeologic environments typical of areas within each region are shown in generalized hydrologic sections and discussed in relation to known characteristics of the areas that provide multiple natural barriers to radionuclide migration and potential for long-term isolation of radioactive waste.

TRANS–PECOS REGION, TEXAS

SUMMARY OF GEOLOGIC AND HYDROLOGIC FACTORS

The Trans-Pecos region has an area of about 27,800 km^2 bordering the Rio Grande in western Texas (pl. 2). The geologic and hydrologic characteristics of the region are summarized in table 1. The hydrogeologic characteristics favorable for waste isolation and corresponding issues of concern for each factor considered in the regional phase of screening are given in table 2.

HYDROLOGIC ENVIRONMENTS

Hydrogeologic environments typical of those in the southwestern part of ground-water unit TP–01 are shown in hydrogeologic section TP–A on plate 1. The environments chosen for discussion are in geologic terrane of Cretaceous and Tertiary sedimentary rocks overlain by volcanic rocks. The Cretaceous rocks overlie thrust sheets of the Marathon complex of Paleozoic age. These sequences have been intruded by middle and late Tertiary silicic igneous rocks in the form of stocks, laccoliths, sills, and dikes.

The ground-water hydrology of the area is affected by the Upper Cretaceous sequence that contains thick shale units. Individual shale units are as thick as 280 m, and aggregate thickness of Upper Cretaceous shale may be as much as 500 m. This sequence is at or near the land surface throughout a large area in ground-water unit TP–01 and probably retards downward movement of water and controls the emergence of many small springs in the area. The ground-water discharge from the deep zones beneath the shale is to the Rio Grande, as shown in hydrogeologic section TP–A (pl. 1), and to Terlingua Creek. Arrows indicate the component of flow direction in the plane of the section. Because all flow is not in the plane of the section, some arrows appear discordant to the regional flow pattern.

Potential host rocks in the area include granitic rocks that form stocks and laccoliths. Laccoliths intruded into the shale section may provide a potential host environment enclosed in a barrier to ground-water flow and radionuclide transport. The thick shale units of the Upper Cretaceous also are considered worthy of examination as host rocks.

Because the shale units restrict downward movement, only a small percentage of ground-water flow enters deeper rock units in the area. Instead, much of the ground water in the region occurs in small, shallow cells and travels only short distances before being discharged as springs at horizons above the shale. In contrast, flow paths from outcropping or subsurface igneous plutons in topographically high areas would be downward and a large part of the flow would follow the underlying Lower Cretaceous carbonate units. Another benefit of the shale in the region is that it also is a barrier to upward flow. This would tend to keep radionuclides in the underlying carbonate rocks from migrating upward to an accessible environment. Traveltimes along deep flow paths are very long, as shown by the hydrogeologic sections modeled in Chapter B of this report series. Ground-water velocity in the carbonate-rock unit (hydrogeologic section TP–A, pl. 1) under a gradient of 0.007 would be 7×10^{-4} to 7×10^{-3} m/d based on a K/ϕ (ratio of hydraulic conductivity to effective porosity) of 1×10^{-1} to 1×10^{0} m/d. Traveltime in the carbonate rocks from the igneous rocks at distances of 20 km, 40 km, and 55 km from the Rio Grande would be 7,800–78,000 yr, 15,700–157,000 yr, and 21,500–215,000 yr, respectively. Traveltimes in the underlying Marathon basin rocks would be two or more times greater because of generally smaller K/ϕ and lower hydraulic gradient. Ground-water velocity in the intrusive rocks having a K/ϕ of 5×10^{-4} to 2×10^{-2} m/d under a hydraulic gradient of 0.01 would be 5×10^{-6} to 2×10^{-4} m/d. Traveltime through a distance of 10 km would be 2×10^{-4} yr.

Retardation potential to radionuclide movement in the ground-water flow system is provided by Upper Cretaceous shale, silicic intrusive rocks, shaley and marly limestone of Early Cretaceous age, and shale in the Marathon facies. Sorption of radionuclides also is favored by the small dissolved-solids concentrations of ground water (generally less than 3,000 mg/L) and calcium bicarbonate or sodium bicarbonate type water.

A small percentage of the area has prospective unsaturated environments in basalt, tuff, and intrusive igneous rocks for isolation of high-level radioactive wastes.

TABLE 1.—*Summary of geologic and hydrologic characteristics of the Trans-Pecos region, Texas*

[km^2, square kilometer; m, meter; mm/yr, millimeter per year; mm, millimeter; km, kilometer; >, greater than; mg/L, milligram per liter]

Characteristic	Ground-water unit			Comments
	TP–01	TP–02	TP-03	
PHYSIOGRAPHY				
Area, in km^2	15,700	4,500	7,600	TP–01 and TP–02 do not have typical Basin and Range physiography. Altitudes of valleys generally are 1,200–1,200 m. Mountain peaks generally are 1,200–2,000 m.
Area of basin fill, in km^2	3,200	1,250	2,750	
Precipitation				Precipitation in the region is 300-360 mm/yr. In the Davis Mountains, (TP–03), precipitation is greater than 450 mm/yr. Precipitation occurs mostly as afternoon thundershowers during during July, August, and September.
Evaporation				Mean-annual free-water-surface evaporation for the region ranges from less than 1,500 to more than 2,000 mm.
POTENTIAL HOST ROCK				
Granitic rocks				
Total outcrop area, in km^2	510	110	80	Unsaturated granitic rocks occur in all three ground-water units.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	350	90	50	Granitic rocks occur as stocks, laccooliths, sills, and dikes of Tertiary age. Granitic rocks include syenite, monzonite, and trachyte.
Unsaturated zone more than 150 m thick:				
Basaltic rocks				
Total outcrop area, in km^2	120	360	0	Basaltic rocks as thick as 130 m crop out in the Stillwell Mountains (TP–01).
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	120	360	0	
Tuffaceous rocks				
Total outcrop area, in km^2	40	100	120	The thickest densely welded ash-flow tuffs occur as intracaldera flows.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	30	90	110	Welded tuffs 140–800 m thick occur in TP–02 and TP–03.
Argillaceous rocks				
Total outcrop area, in km^2	710	0	0	Argillaceous rocks 200–450 m thick occur mostly in the southern part of TP–01.
Total area, in km^2, contiguous outcrops that are more than 6.5 km^2.	660	0	0	

TABLE 1.—*Summary of geologic and hydrologic characteristics of the Trans-Pecos region, Texas*—Continued

Characteristic	Ground-water unit TP–01	TP–02	TP–03	Comments
POTENTIAL HOST ROCK—Continued				
Areas underlain by unsaturated basin fill more than 150 m thick.				
Total outcrop area, in km^2	70	110	230	Unsaturated basin fill at least 150 m thick occurs in small, discontinuous areas.
Total outcrop area of potential host rock (does not include argillaceous or unsaturated basin fill).				
Total surface area, in km^2	1,140	570	200	Argillaceous rocks are of sufficient thickness and extent to be considered as potential host rocks in some areas of TP–01.
Total surface area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	500	540	160	Argillaceous rocks are continuous throughout the subsurface in parts of TP–01 and are potential barriers to nuclide migration.
QUATERNARY TECTONIC ACTIVITY				
Strain release				
Strain release of more than 10 occurs in unit.	NO	NO	YES	Two recorded earthquakes near Valentine in TP–03 account for strain release greater than 10.
Percent of outcrop area of potential host rock within 10 km of area where strain release is more than 10.	0	0	30	
Vertical crustal movement				
Long term				
Uplift of more than 4 m per 10 yr occurs within unit.	NO	NO	NO	The long-term rate of vertical crustal movement is 1–2 m per 10^4 yr.
Percent of outcrop area of potential host rock with uplift of more than 4 m per 10^4 yr.	0	0	0	
Short term				
Uplift of more than 4 mm/yr, based on geodetic leveling.	NO	NO	YES	Short-term rates (within the last 50 yr) of apparent vertical crustal movement as great as 6 mm/yr have been reported.
Percent of outcrop area of potential host rock with movement of more than 4 mm/yr, based on geodetic leveling.	0	0	0	

TABLE 1.—*Summary of geologic and hydrologic characteristics of the Trans-Pecos region, Texas*—Continued

Characteristic	Ground-water unit TP–01	TP–02	TP–03	Comments
QUATERNARY TECTONIC ACTIVITY—Continued				
Quaternary faults				
Quaternary fault(s) occurs in unit	NO	YES	YES	Relatively few Quaternary faults have been mapped in the region.
Percent of outcrop area of potential host rock within 10 km of Quaternary fault.	0	10	20	
Heat flow				
Heat flow more than 2.5 heat flow units occurs within unit.	NO	YES	NO	
Percent of outcrop area of potential host rock within 10 km of area where heat flow is more than 2.5 heat flow units.	0	20	0	
Quaternary volcanism				
Quaternary volcanism occurs within unit.	NO	NO	NO	
Percent of outcrop area of potential host rock within 10 km of area where Quaternary volcanism has occurred.	0	0	0	
GEOMORPHIC PROCESSES				Lowering of sea level during a glacial period probably will not cause entrenchment of the Rio Grande. However, entrenchment rate may change due to climatic change.
GROUND-WATER HYDROLOGY				
Ground-water flow conditions				
Common values of relative ground-water traveltime near the water table from areas of potential host rock to natural discharge areas.	5–20	>20	>20	Relative ground-water traveltimes from potential host rocks to natural discharge areas in selected deep sections range from 10^4 to 10^7. Geothermal springs occur at or near the Rio Grande in TP–01. Cold springs occur at intermediate points on flow paths from divides to major discharge areas.
Longest relative traveltime near the water table from areas of potential host rock to natural discharge areas.	20–50	100–200	100–200	Traveltimes in shale units have not been estimated. Ground-water velocities in shale are extremely slow. Hydrologic control for estimating relative traveltime of ground water is very sparse in TP–01 and TP–03.

TABLE 1.—*Summary of geologic and hydrologic characteristics of the Trans-Pecos region, Texas*—Continued

Characteristic	Ground-water unit TP–01	TP–02	TP–03	Comments
GROUND–WATER HYDROLOGY—Continued				
Changes in boundary conditions				
Part of area inundated by Pleistocene lake.	NO	NO	NO	Change to pluvial climate may result in increased recharge and a rise in ground-water level. Recurrence of a lake in the Salt Flat will raise the base level of discharge in TP–03.
Percent of outcrop area of potential host rock inundated by Pleistocene lake.	0	0	0	
Ground-water supply				Ground-water supplies are developed from basin fill, carbonate rocks, tuffs, and basaltic rocks. Ground- water development has caused a major depression in the water table in the northwestern part of TP–03.
GEOCHEMISTRY				
Water quality				
Area, in km^2, of basin fill where ground water contains dissolved-solids concentration of:				Ground water generally contains less than 3,000 mg/L dissolved solids. Dissolved-solids concentrations greater than 3,000 mg/L are associated with evaporite deposits in Salt Flat.
Less than 500 mg/L	400	400	2,050	
500–1,000 mg/L	250	400	100	
1,000–3,000 mg/L	550	450	500	
3,000–10,000 mg/L	0	0	100	
More than 10,000 mg/L.	0	0	0	
Retardation of radionuclides				Deep flow paths travel through long distances of carbonate rocks. These rocks commonly contain marl that may retard radionuclide migration.
MINERAL AND ENERGY RESOURCES				
Percent of potential-host-rock outcrop area coincident with mineral resource area.	13.4	5.3	10.0	There is no current mineral- or energy-resource production in the region.

TABLE 2.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Trans Pecos region, Texas*

[m, meter; yr, year; mm/yr, millimeter per year; mg/L, milligram per liter]

Potentially favorable hydrogeologic factors	Issues of concern and study needs
POTENTIAL HOST ROCKS	
Some intrusive rocks occur as stocks. Thick sills and laccoliths intruding argillaceous rocks occur in ground-water unit TP–01.	Many intrusive rocks occur as sills, dikes, and laccoliths of unknown thickness and extent.
	Field studies are needed to define thickness and stratigraphic relationships of granitic rocks.
	Field studies are needed to define thickness of unsaturated zone and lithology of extrusive rocks.
Unsaturated basalts and tuffs occur in ground-water units TP–01, TP–02, and TP–03.	Saturated tuffaceous and basaltic rock beneath unsaturated zone may have potential for water-supply development.
Argillaceous rocks occur in ground-water unit TP–01.	Some argillaceous rocks contain coarse-grained interbeds. Studies are necessary to define lithologic and hydrologic character.
QUATERNARY TECTONIC ACTIVITY	
Known tectonic activity in the region is limited, with few Quaternary faults, slow rate of tectonic uplift, few earthquakes, no Quaternary igneous activity, and slight to moderate heat flow.	Additional Quaternary faults might be located by field studies.
GEOMORPHIC PROCESSES	
Stream entrenchment at a maximum rate equal to the rate of long-term vertical crustal movement, 1–2 m per 10^4 yr, would not reduce effectiveness of a waste-isolation environment at a depth as great as 300 m during 100,000 yr.	
Large, short-term local rates of vertical uplift are not expected to persist for periods long enough to affect the integrity of a repository.	Short-term, local rate of vertical uplift could be as much as 6 mm/yr.
GROUND-WATER HYDROLOGY	
Ground-water flow conditions	
Relative ground-water traveltimes from potential host rocks to natural discharge areas are very long.	Subsurface data on geologic framework and data on hydraulic properties of rocks and hydraulic gradient are few.
Thermal springs indicative of intermediate discharge points at or near major streams do not occur.	

TABLE 2.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Trans Pecos region, Texas*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GROUND-WATER HYDROLOGY—Continued	
Ground-water flow conditions—Continued	
Slow ground-water velocities in argillaceous rocks and fine-grained interbeds are barriers to ground-water movement.	
Changes in boundary conditions	
Lowering of sea level would not appreciably affect base level of ground-water discharge to Rio Grande.	Increase in ground-water level during pluvial cycle will decrease area of potential host rocks in the unsaturated zone.
	Inundation of Salt Flat will decrease ground-water traveltime at shallow depths in ground-water unit TP–03.
Entrenchment of the Rio Grande during a pluvial cycle will lower ground-water discharge level and tend to attenuate effects of increased recharge.	Increase in hydraulic gradients will increase ground-water velocities.
Water Supply	
Crystalline rocks generally are not explored to depths greater than 100 m for water supply.	Small to moderate quantities of water are available to wells in indurated rocks.
	Large quantities of water are available locally from basin fill and volcanic rocks.
	Ground-water production has caused a depression in the water table in the northwestern part of ground-water unit TP–03.
GEOCHEMISTRY	
Water quality	Ground water generally contains less than 3,000 mg/L dissolved solids.
Retardation of radionuclides	
Deep flow paths extend long distances through carbonate rocks. These rocks commonly contain marl that may retard radionuclide migration.	
MINERAL AND ENERGY RESOURCES	
There is no current mineral production from the region.	Because of past exploration for minerals, geothermal resources, uranium, and oil and gas, there may be future exploration for mineral and energy resources.
There is no oil or gas production from the region.	
Potential for geothermal production is minimal.	Thermal ground water may have potential for use in space heating.

The area is quiet tectonically. Warm springs near the Rio Grande reflect a minor volume of relatively deep convective flow. Maximum anticipated rates of erosion would not jeopardize a repository at a depth of 300 m during 100,000 yr. A change to a pluvial climate probably would not adversely affect waste-isolation environments in the saturated zone; the unsaturated zone might be decreased in area by an increase in recharge rate.

Though ground water generally is suitable for most uses, its availability for supplies and, therefore, the risk of human intrusion is limited, especially in shale and igneous rocks. Large-scale mineral and energy resources have not been developed; however, there may be future exploration and development.

Hydrogeologic environments that occur in ground-water units TP–02 and TP–03 are depicted in hydrogeologic section TP–B (pl. 1). Some aspects of this section also are typical of the western edge of ground-unit TP–01. The area represented by section TP–B lies northwest of the Marathon thrust belt and contains Precambrian, Paleozoic, and Cretaceous sedimentary rocks overlain by Tertiary tuff and basalt and by Tertiary and Quaternary basin fill. Rocks of older Tertiary, Mesozoic, and pre-Mesozoic age are intruded by a Tertiary granitic pluton. A caldera, though invaded and uplifted by the Tertiary plutonic mass, still contains remnants of welded tuffs.

Potential host media along section TP–B (pl. 1) include saturated and unsaturated granitic rock and unsaturated volcanic rocks. Precipitation, which occurs mostly in summer as afternoon thundershowers, is greatly exceeded by the free-water-surface evaporation; this relationship enhances the unsaturated zone as a potential waste medium.

The flow path of ground water is from the water-table divide, approximately coincident with the topographic divide, to the Rio Grande and to the Salt Flat. The flow path is long and the gradient is low, 0.007, to Salt Flat, and consequently the traveltime is long. The fastest velocity of ground water from the caldera intrusions to Salt Flat and to the Rio Grande occurs in carbonate rocks. Assuming a gradient of 0.007 and a K/ϕ of 1×10^{-1} to 1×10^{0} m/d, the ground-water velocity in carbonate rocks would be 7×10^{-4} to 7×10^{-3} m/d. Traveltime through a distance of 100 km would be 4×10^{5} to 4×10^{4} yr. The velocity in the igneous rock would be slower, about 1.4×10^{-4} to 1.4×10^{-3} m/d, assuming a gradient of 0.007 and a K/ϕ of 2×10^{-2} to 2×10^{-1} m/d. Though the flow path is short and the gradient slopes to the Rio Grande, hydrogeologic sections in Chapter B of this series indicate that traveltimes probably are greater than 100,000 yr.

Retardation of radionuclides would be affected by clay minerals in the granite and tuff and by shaley zones in the clastic and carbonate sedimentary rocks. Sorption of radionuclides by the earth materials would be favored by small dissolved-solids concentration in the water of the flow system and by calcium and sodium bicarbonate type water.

Tectonically, the area has had sizable earthquakes, recent uplift, and faulting in the basin area, all of which occurred many tens of kilometers from potential host media. Such tectonism, being well outside potential host-rock areas, would not adversely affect prospective repository areas. Maximum anticipated erosion rates would not affect the integrity of a repository at a depth of 300 m during 100,000 yr. A change to pluvial conditions would possibly decrease the thickness of the unsaturated zone. The response time and amount of potential water-level change due to climatic change need to be considered in evaluation of the unsaturated-zone environment.

Ground-water supplies are limited from intrusive igneous rocks. Saturated volcanic rocks beneath the thick unsaturated zone may be a prospective water supply; however, large water supplies are available from the basin fill. Mineral and energy resources, if present, are not currently produced. There may be future exploration for mineral and energy resources.

CONCLUSIONS

Potentially favorable factors in the three ground-water units in the Trans-Pecos region support further search for suitable waste-isolation environments. Potential host rocks are primarily igneous intrusive rocks and thick intracaldera tuffs in the saturated and unsaturated zones and unsaturated tuffs and basalts. In ground-water unit TP–01, igneous intrusives in thick argillaceous units provide multiple-barrier prospects for further study. Ground-water traveltimes from many areas of potential host rock to discharge areas are projected on the basis of current hydrologic conditions to be several tens of thousands to 100,000 yr. With a recurrence of Pleistocene conditions the velocity would increase in proportion to the increase in gradient. A recurrence of Pleistocene hydrologic conditions would have the greatest effect in raising ground-water level, thereby decreasing the thickness and extent of the unsaturated zone. Chemical retardation of radionuclides by sorption on clay minerals in argillaceous and intrusive rocks will likely isolate radionuclides for long periods in many areas of the region. The generally limited Quaternary tectonic activity appears to promise stability for 10,000–100,000 yr. The more clearly defined issues of concern are the general widespread availability of

potable ground water and the possibility of exploration for mineral and energy resources.

Based on guidelines established in Chapter A and on the available published and unpublished data, it appears that the abundance of host rock in the western part of ground-water unit TP–01 makes it more favorable than the eastern part of the unit for future study. Tuffaceous units in the northern part of ground-water unit TP–02 generally are thin. Thick tuff and basalt occur in the southern part of the unit but the traveltimes are shorter. Long travel-times from unsaturated tuffs and granites in the southern part of ground-water unit TP–03 make this part of the unit relatively favorable although host-rock exposures are small.

RIO GRANDE REGION, NEW MEXICO AND TEXAS

SUMMARY OF GEOLOGIC AND HYDROLOGIC FACTORS

The Rio Grande region has an area of about 35,000 km^2 east of the Rio Grande in New Mexico and Texas (pl. 3). Geologic and hydrologic characteristics of the region are summarized in table 3. Potentially favorable factors for waste isolation and corresponding issues of concern for each factor considered in the regional phase of screening are given in table 4.

HYDROGEOLOGIC ENVIRONMENTS

Hydrogeologic environments typical of the Rio Grande region which may be prospective for further study are discussed below. Data are not available for assessment of performance of specific sites as isolation environments for high-level radioactive waste. Therefore, specific sites in the region are not identified in the scenarios.

Some hydrogeologic environments typical of those in ground-water unit RG–01 can be seen in section RG–A (pl. 1), which shows Precambrian crystalline and metasedimentary rocks, and Paleozoic and Cretaceous sedimentary rocks that have been block-faulted and intruded by Tertiary igneous rocks. The basin area contains fill of Tertiary and Quaternary sediments and volcanic rocks. Igneous intrusive rocks, the principal candidates for host rocks, are in the form of stocks, sills, and possibly laccoliths. Potential host rocks occur in areas where ground-water recharge is relatively low and flow paths are downward. The Paleozoic and Cretaceous sequence contains fine-grained clastic rocks and evaporites that retard the flow of ground water. Also within this sequence are argillaceous rocks which have potential to retard radionuclide migration. Gypsum and anhydrite in the Permian section are responsible for moderate to high concentrations of sulfate-type water in much of the flow system and in the basin fill. The poor quality of water and the generally fine grained nature of the basin fill in New Mexico has tended to limit large-scale development of ground water. Ground-water unit RG–01 contains large areas of unsaturated basin fill.

Tectonism is evidenced by the Malpais, a Quaternary lava flow in the north-central part of ground-water unit RG–01; Quaternary range-bounding faults bordering the western side of RG–01; and by abundant Quaternary faults in the southern New Mexico and northern Texas part of RG–01. Quaternary faults are of concern where fault-line trends align with potential repository areas. Otherwise Quaternary faults showing displacement in basin fill do not directly affect the surface occurrences of potential repository rock. The effect on ground-water flow by faults in the southern, downstream end of the flow system is minimal because the area is near the discharge area; time of travel to this area should be long and beyond immediate and midterm concern. Although tension faults tend to "heal" or become less permeable with time, some of the faults may permit passage of water from depth into the basin fill.

Geothermal wells in basin fill in the southern New Mexico and Texas parts of ground-water unit RG–01 indicate upwelling of geothermal ground water from deep zones through zones of fracture permeability or possibly along faults.

Thick argillaceous sections and laharic breccias may be candidates for study as host rocks. Although these rocks are of low permeability, they are not uniformly homogeneous. Shales of Paleozoic age may contain permeable or soluble interbeds of evaporites that would render them less desirable as host media.

Ground-water flow from a potential repository in an igneous-rock mass would be downward, thence lateral toward the Rio Grande. Flow times are relatively long and retardation of radionuclides would be afforded by the rocks in the flow paths. Barriers to flow and radionuclide transport are present as thick shales, argillaceous units, and laharic breccias. Faults along the front of the ranges in the eastern part of ground-water unit RG–02 are in the general area of downward ground-water movement. Permeable fault zones would tend to direct ground water flow to deeper zones. Permeable faults on the western side of the basin convey ground water upward to shallower zones as indicated by thermal wells and springs in this area.

Maximum anticipated rates of erosion would not affect a repository at a depth of 300 m during 100,000 yr. A change in climate to pluvial conditions would not greatly affect a saturated repository environment in ground-water unit RG–01. The thick unsaturated zone (more than 150 m) in the area is not of great areal extent, and an increase in water level would reduce the area of the prospective repository areas in the unsaturated zone.

TABLE 3.—*Summary of geologic and hydrologic characteristics of the Rio Grande region, New Mexico and Texas*

[km^2, square kilometer; m, meter; mm/yr, millimeter per year; km, kilometer; mg/L, milligram per liter]

Characteristic	Ground-water unit		Comments
	RG–01	RG–02	
PHYSIOGRAPHY			
Area, in km^2	22,100	12,900	The altitudes of the valley surfaces are generally 1,100–1,500 m. Mountains are generally 1,500–2,400 m; peaks over 2,900 m high occur in RG–02.
Area of basin fill,in km^2	11,200	6,200	
Precipitation			Precipitation generally is 200–400 mm/yr in the basins and greater than 600 mm/yr in the Sacramento Mountains.
Evaporation			Mean-annual free-water-surface evaporation ranges from approximately 1,500 mm/yr in the northern part of RG–01 to greater than 2,000 mm/yr in the southern part of RG–02.
POTENTIAL HOST ROCK			
Granitic rocks			
Total outcrop area,in km^2	510	410	
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	410	100	
Unsaturated zone more than 150 m thick:			
Basaltic rocks			
Total outcrop area, in km^2	0	0	Basaltic rocks as thick as 100 m occur in RG–02. Unsaturated zone commonly is less than 150 m thick.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	0	0	
Tuffaceous rocks and laharic breccia.			
Total outcrop area, in km^2	0	0	Ash-flow tuffs as thick as 600 RG–02. Unsaturated zone commonly is less than 150 m. Laharic breccias may be as much as 600 m thick in the southern part of RG–02.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	0	0	
Argillaceous rocks			
Total outcrop area, in km^2.	460	470	Paleozoic argillaceous rocks occur in the northern part of the region and range in thickness from near zero to 550 m.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	450	420	Cretaceous shales as thick as 150–760 m crop out in RG–01 and RG–02.
Areas underlain by unsaturated basin fill more than 150 m thick.			
Total outcrop area, in km^2	430	0	
Total outcrop area, in km^2, of potential host rock (does not include argillaceoous rocks or basin fill).			Argillaceous rocks are of sufficient thickness and extent to be considered potential host rock in the region.

TABLE 3.—*Summary of geologic and hydrologic characteristics of the Rio Grande region, New Mexico and Texas*—Continued

Characteristic	Ground-water unit RG–01	Ground-water unit RG–02	Comments
POTENTIAL HOST ROCK—Continued			
Total ourcrop area, in km^2, of potential host rock (does not include argillaceous rocks or basin fill)—Continued			
Total surface area, in km^2	510	140	
Total surface area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	410	100	
QUATERNARY TECTONIC ACTIVITY			
Strain release			
Strain release of more than 10 occurs in unit.	NO	YES	Strain release associated with the Socorro uplift is relatively high in northwestern part of RG–02.
Percent of outcrop area of potential host rock within 10 km of areas where strain release is more than 10.	0	10	
Vertical crustal movement			
Long term			The long-term rate of vertical crustal movement is less than 2 m per per 10^4 yr over most of the region. Uplift associated with the Socorro uplift, as determined from geodetic leveling, is relatively high in the northwestern part of RG–02.
Uplift of more than 4 m per 10^4 yr occurs within unit.	NO	YES	
Percent of outcrop area of potential host rock with uplift of more than 4 m per 10^4 yr.	0	80	
Short term			
Vertical crustal movement of more than 4 mm/yr based on geodetic leveling.	NO	YES	
Percent of outcrop area of potential host rock with movement more than 4 mm/yr based on geodetic leveling.	0	0	
Quaternary faults			
Quaternary fault(s) occurs in unit.	YES	YES	Dense Quaternary faults occur in the southern part of RG–01, near lat 32° N.
Percent of outcrop area of potential host rock within 10 km of Quaternary fault.	60	10	
Heat flow			
Heat flow more than 2.5 heat flow units occurs in unit.	YES	YES	
Percent of outcrop area of potential host rock within 10 km of area where heat flow is more than 2.5 heat flow units.	20	20	
Quaternary volcanism			
Quaternary volcanism occurs within unit.	YES	YES	
Percent of outcrop area of potential host rock within 10 km of area where Quaternary volcanism has occurred.	5	50	
GEOMORPHIC PROCESSES			Climatic change may cause entrenchment of trunk streams.

TABLE 3.—*Summary of geologic and hydrologic characteristics of the Rio Grande region, New Mexico and Texas*—Continued

Characteristic	Ground-water unit RG–01	Ground-water unit RG–02	Comments
GROUND-WATER HYDROLOGY			
Ground-water flow conditions			
Common values of relative ground-water traveltime near the water table from areas of potential host rock to natural discharge areas.	1–5;10–20	1–5	Flow paths in the southern part of RG–01 and components of most deep flow paths discharge to a pumping center near El Paso. Few large springs occur in each ground-water unit. Most flow paths are unaffected.
Longest relative traveltime near the water table from areas of potential host rock to natural discharge areas.	20–50	1–5	
Changes in boundary conditions			
Part of area inundated by Pleistocene lake	YES	NO	Change to pluvial climate may result in increased recharge and a rise in ground-water level.
Percent of outcrop area of potential host rock inundated by Pleistocene lake.	0	0	
Ground-water supply			Basin-fill deposits, basaltic and tuffaceous rocks, and sandstones may yield small to moderate quantities of water. Basin fill locally yields large quantities of water. Ground-water withdrawal has caused a major depression in the water table in the southern part of RG–01 near El Paso.
GEOCHEMISTRY			
Water quality			
Area, in km^2, of basin fill containing dissolved-solids content of:			Ground water contains greater than 1,000 mg/L dissolved solids in most of the basin fill.
Less than 500 mg/L	500	1,500	
500–1,000 mg/L	900	1,150	
1,000–3,000 mg/L	5,200	3,250	
3,000–10,000 mg/L	3,850	300	
More than 10,000 mg/L	750	0	
Retardation of radionuclides			Most deep flow paths in RG–01 and RG–02 travel through significant thicknesses of fine-grained alluvium to natural discharge areas.
MINERAL AND ENERGY RESOURCES			
Percent of potential-host-rock outcrop area coincident with mineral resource area.	67	79	Most mineral districts are small and currently inactive. Organ and Orogrande districts each have produced more than $1 million in metals. Four coal fields are present in the region. Majority of mining has been intermittent due to structural complexities of the beds. There is no oil or gas production in the region. No known geothermal resource areas occur in the region. There is possible potential for brine mining.

TABLE 4.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Rio Grande region, New Mexico and Texas*

[m, meter; yr, year; mm/yr, millimeter per year; mg/L, milligram per liter]

Potentially favorable hydrogeologic factors	Issues of concern and study needs
POTENTIAL HOST ROCKS	
Abundant granitic stocks occur in ground-water units RG–01 and RG–02.	Precambrian granitic rocks are locally fractured and foliated.
Granitic rocks occurring as stocks, sills, and laccoliths crop out in the mountain ranges.	Extents of sills and laccoliths are not well known, and some may be of insufficient size for potential host rocks. Granitic rocks are locally highly fractured and sheared.
Laharic breccias of low permeability may form potential host media.	Laharic breccias have not been examined as potential host media.
Unsaturated basalts, ash-flow tuffs, and laharic breccias occur in maximum thicknesses possibly as much as 100, 600, and 700 m, respectively.	Unsaturated volcanic rocks are of limited areal distribution.
Dominantly argillaceous rocks occur in maximum thicknesses of 550–760 m.	Argillaceous rocks locally contain interbeds of evaporites and coarse-grained sediments.
	Potential host rocks are not abundant; site studies are needed to determine their suitability.
QUATERNARY TECTONIC ACTIVITY	
The region has few Quaternary faults.	Quaternary range-front faults border the western side of the southern Tularosa basin (ground-water unit RG–01). Dense faulting occurs in the southern part of ground-water unit RG-01.
Vertical crustal movement and seismic activity is small, except near the Socorro uplift to the northwest of the region.	Strain release more than 10 and short-term uplift associated with the Socorro uplift occur in the northwestern part of ground-water unit RG–02.
Geothermal heat flow is less than 2.5 heat flow units in most of the region.	
Quaternary volcanic activity is limited to a few centers in the northern parts of ground-water units RG–01 and RG–02.	Quaternary volcanic activity occurs within 10 km of potential host rocks in parts of ground-water units RG–01 and RG–02.
GEOMORPHIC PROCESSES	
Denudation of the surface at a maximum rate equal to the rate of long-term vertical crustal movement, 2 m per 10^4 yr, would not reduce effectiveness of a waste-isolation environment at a depth as shallow as 300 m over a period of 100,000 yr.	
Larger, short-term local rates of uplift are not expected to persist for periods long enough to affect integrity of a repository.	Short-term, local vertical uplift as great as 4 mm/yr occurs near northwestern part of ground-water unit RG–02.

TABLE 4.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Rio Grande region, New Mexico and Texas*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GROUND-WATER HYDROLOGY	
Ground-water flow conditions	
Relative ground-water traveltimes in deep sections from potential host rocks to natural discharge areas are very long.	Subsurface data on hydrologic properties of rocks and hydraulic gradients are sparse.
Argillaceous rocks, laharic breccias, and fine-grained interbeds are barriers to ground-water movement.	
Changes in boundary conditions	Increase in hydraulic gradients would increase ground-water velocities.
	Recurrence of Pleistocene Lakes Otero and Trinity will decrease ground-water traveltime at shallow depths in parts of ground-water units RG–01 and RG–02.
Entrenchment of Rio Grande during pluvial cycle will tend to lower ground-water level and attenuate rise of ground-water level due to increase in recharge.	Increase in ground-water level during pluvial cycle will potentially decrease area of potential host rock in the unsaturated zone.
Water supply	
Potential host rocks, crystalline rocks, laharic breccias, and argillaceous rocks, are negligible to minor sources of water supply.	Basin-fill deposits, basaltic and tuffaceous rocks, and sandstones locally may yield small to moderately large quantities of water.
	Significant ground-water withdrawal occurs in the southern part of ground-water unit RG–01 near El Paso.
GEOCHEMISTRY	
Water quality	
Water quality is poor, containing greater than 1,000 mg/L dissolved solids in many of the basin-fill deposits.	
Ground water at depth in consolidated rocks may contain greater than 3,000 mg/L dissolved solids.	
Retardation of radionuclides	
Most deep flow paths in both ground-water units travel through significant thicknesses of fine-grained alluvium to reach natural discharge areas. Retardation of radionuclides is relatively high in fine-grained alluvium.	Most deep flow paths travel through carbonate rocks, which may or may not retard nuclide migration, depending on the mineralogy in the carbonate.
MINERAL AND ENERGY RESOURCES	
Most mineral districts are small and currently inactive. There is no oil or gas production in the region.	There may be future exploration for energy and mineral resources.
Potential for geothermal energy production is low.	Thermal ground water may have potential for use in space heating.

There is no current mineral, oil, or gas production in the unit. Geothermal resources of the southern part of the area may have potential for space heating.

Hydrogeologic environments typical of ground-water unit RG–02 of the Jornada del Muerto are shown in section RG–B (pl. 1). The geologic structure of the area, as shown in section RG–B (pl. 1), is a broad synclinal basin. Precambrian basement rocks underlie the basin. The sedimentary sequence overlying the basement rocks consists of Paleozoic, Mesozoic, and Cenozoic clastic, evaporitic and volcanic rocks having a maximum thickness of 2,500–3,000 m. Potential host rocks are primarily silicic igneous stocks, laccoliths, or sills, most of which crop out in the mountain ranges.

Ground-water traveltimes from the ground-water divides to the Rio Grande in ground-water units RG–01 and RG–02 (pl. 1) are very great because of the low hydraulic gradient, long flow path, and general low permeability of the rocks. Ground-water velocity in the igneous plutons at the divides is estimated to be 1.5×10^{-4} to 6×10^{-4} m/d under a gradient of 0.03 with a K/ϕ (ratio of hydraulic conductivity to effective porosity) of 5×10^{-4} to 2×10^{-2} m/d. Traveltime through 10 km of the igneous rock would accordingly be from 1.8×10^{6} to 4.5×10^{4} yr. Ground-water velocity in the section from the igneous rock to the Rio Grande is probably greatest through the carbonate rocks. Under a gradient of 0.003, the velocity in carbonate rocks would be 3×10^{-3} to 3×10^{-4} m/d for K/ϕ of 1×10^{-1} to 1×10^{0} m/d, and the travel time through a distance of 30 km would be 2.7×10^{4} to 2.7×10^{5} yr.

The ground-water velocity upward from deep flow paths to the discharge areas is very small, as indicated by hydraulic gradients (less than about 4×10^{-4}) from the analyzed cross-sectional models in the characterization report (Professional Paper 1370, Chapter C), and by the low permeability of the argillaceous bedrock units, the lower part of the basin fill, and, in ground-water unit TP–02, the laharic breccias.

Quaternary tectonism in ground-water unit RG–02 includes local areas of basalt flows and faulting. Seismic strain release and short-term vertical uplift are relatively high in the northwestern part of the unit associated with the Socorro uplift located west of the Rio Grande. These tectonic factors have little effect on waste isolation in a crystalline-rock repository in the eastern part of the basin.

Ground-water supplies in the basin are limited by the low permeability of both the basin fill and the Paleozoic rocks and by the poor quality of the ground water in the Paleozoic rocks. There is no current mineral, oil, or gas production in ground-water unit RG–02. Geothermal resources of the western part of the area may have potential for space heating.

The recurrence of pluvial conditions would increase recharge and reactivate filling of Pleistocene Lake Trinity in the northern part of the Jornada del Muerto. The lake would probably impose an intermediate discharge area on the ground-water flow that now discharges to the Rio Grande. Ground-water flow at depth and repositories designed for the saturated zone may not be greatly affected by pluvial conditions. Though the ground-water flow velocities would increase, traveltime from repository rocks in the San Andres Mountains would be very great (more than 100,000 yr).

CONCLUSIONS

Many potentially favorable factors for waste isolation in the Rio Grande region indicate areas for further study. Potentially favorable host rocks consist of intrusive igneous masses located near the head of long ground-water flow systems. Natural barriers are provided by fine-grained clastic and crystalline rocks of low permeability and by sorptive surfaces in flow systems with low gradients. Quaternary tectonism must be considered if future studies are made in the Rio Grande region. Possible adverse effects can be minimized by assessments of Quaternary tectonic conditions at alternative locations. The ground water in much of the region is of poor quality for most uses.

Saturated and unsaturated intrusive rock masses and unsaturated tuffaceous and basaltic rocks with potential as host media occur in the mountain ranges of both ground-water units, RG–01 and RG–02, of the Rio Grande region. The unsaturated zone is of limited extent and may be reduced by recurrence of pluvial conditions. The accompanying decrease in saturated thickness would be minimal in highly transmissive rocks such as fractured tuff and basalt. The properties of laharic breccias in ground-water unit RG–02 have not been examined critically as prospective host rocks; however, in favorable hydrogeologic environments, laharic breccias may be prospective for study. Argillaceous rocks in the region deserve qualified recognition as potential host rocks because they contain interbeds of evaporites and coarse-grained sediments that tend to reduce homogeneity or increase permeability. Prospective environments would be enhanced by the presence of thick argillaceous and laharic rocks and fine-grained basin-fill deposits which would afford hydraulic and geochemical barriers to radionuclide transport. Ground-water traveltimes from potential host rocks to natural discharge areas are projected under present and pluvial conditions to be greater than 100,000 yr. Chemical retardation will increase the traveltime of radionuclides for long periods of time in many parts of the region. Quaternary tectonic activity is relatively low, but is of

local concern. It will probably not interfere seriously with stability of waste-isolation environments. Ground water generally is of poor quality, thereby reducing the chances for future human intrusion.

The long traveltimes and general abundance of granitic exposures in ground-water unit RG–01 and in the northern part of ground-water unit RG–02 suggest prospects for future search for specific environments in these units. The very extensive unsaturated zone in the southeastern part of ground-water unit RG–01 would be of interest for environments in thick alluvium. The southern part of ground-water unit RG–02, however, has a general lack of host rock and paucity of unsaturated section. This, combined with probable short traveltimes from granitic rocks near the Rio Grande, appear to limit prospects for further study in the southern part of ground-water unit RG–02.

SONORAN REGION, ARIZONA

SUMMARY OF GEOLOGIC AND HYDROLOGIC FACTORS

The Sonoran region of Arizona has an area of about 48,900 km^2 east of the Colorado River (pl. 4). The geologic and hydrologic characteristics of the region are summarized in table 5. The potentially favorable factors for waste isolation and corresponding issues of concern for each factor considered in the regional phase of screening are given in table 6.

HYDROGEOLOGIC ENVIRONMENTS

Hydrogeologic environments typical of the Sonoran region, Arizona, which may be prospective for further study, are discussed below. Data are not available for assessment of the performance of specific sites as isolation environments for high-level radioactive waste. Therefore, specific sites in the region are not identified in the scenarios.

Hydrogeologic environments which occur in the region are shown in hydrogeologic sections in plate 1. Tertiary and Cretaceous granitic basement rocks are overlain by Tertiary and Quaternary volcanic rocks and unconsolidated basin fill. Extensional faulting in middle Tertiary time produced ranges and basins. Basin-and-range faulting in this region is older than similar faulting to the north in Nevada. This is evident in the southern part of the region where there is mature erosion of ranges, large areas of basin and alluvial fill, and integrated surface drainage (hydrogeologic section SA–A, pl. 1). Hydrogeologic section SA–B in plate 1 represents basins that formerly had interior drainage. Most basins in the region are open to the Gila or Colorado Rivers.

The arid climate has a dominant effect on groundwater hydrology. The average annual precipitation is as little as 100 mm/yr; average annual evaporation is 10–20 times the annual precipitation. In contrast to mountain ranges elsewhere in the Basin and Range province, many of the ranges in the southern Sonoran region of Arizona are low, commonly less than 1,000 m above the basin floors. In much of the area the low ranges tend to minimize the orographic effect of the mountains in receiving more precipitation than the basins. Recharge in much of the region is thus believed to be very small. In contrast, the western part of ground-water unit SA–07 has higher ranges which receive greater precipitation and probably more recharge than the remainder of the region.

Potential host media in the region include salt, saturated and unsaturated granitic rocks, and unsaturated basalt, tuff, and basin fill. The areal extent of the thick (more than 150 m) unsaturated zone is poorly known but sufficiently large to hold promise for further study.

Ground-water traveltimes along deep flow paths from potential host rocks near ground-water divides to natural discharge areas are very long. Ground- water traveltime is retarded by small hydraulic gradients and low permeability of the crystalline rocks, especially at depths where fracture permeability is probably low, and by fine-grained, indurated, lower parts of the basin fill. The fine-grained Miocene Bouse Formation of marine origin is believed to be present in the downstream parts of the basins on the Colorado and Gila Rivers, and their major tributaries, such as the environment shown in hydrogeologic section SA–A (pl. 1). Clay minerals in the basin fill and in weathered volcanic, metamorphic, and igneous rocks probably would afford significant retardation of radionuclide transport.

Ground-water velocities in deep igneous intrusions at depth with a K/ϕ (ratio of hydraulic conductivity versus effective porosity) of 5×10^{-4} to 2×10^{-2} m/d and a hydraulic gradient of 0.03 would be from 1.5×10^{-5} to 6×10^{-4} m/d. At this rate, traveltime through 10 km of igneous intrusive rocks would be 1.8×10^{6} to 4.5×10^{4} yr. Ground-water velocities in shallow metamorphic rocks with a K/ϕ of 5×10^{-2} to 4×10^{0} m/d and a hydraulic gradient of 0.003 probably would be within the range of 1.5×10^{-4} to 1.2×10^{-10} m/d. The ground-water traveltime along deep flow paths from igneous intrusions near the ground-water divides to natural discharge areas, under these assumed hydraulic conditions, would greatly exceed 10^{6} yr. Large thermal or cold springs indicating anomalously great hydraulic conductivity are rare.

The area adjacent to the Salton Sea trough to the southwest and an area near Lake Mead at the northern end of the region have recorded significant seismic

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*

[km^2, square kilometer; m, meter; mm/yr, millimeter per year; mg/L, milligram per liter]

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
PHYSIOGRAPHY											
Area, in km^2	3,400	4,100	4,100	2,700	1,900	9,200	13,400	3,300	4,200	2,600	All ground-water units, except parts of SA–07, drain to the Colorado, Gila, or Bill Williams Rivers.
Area of basin fill, in km^2.	1,900	1,800	2,350	1,300	1,100	4,250	3,000	1,500	1,900	1,000	Most mountain ranges are 1,000 m above the valley floors. Most basins are 150–300 m above sea level.
Precipitation											Precipitation in most of the area is 100–200 mm/yr; in parts of SA–08 and and SA–09, it is 200–300 mm/yr; in parts of SA–08, it is more than 500 mm/yr.
Evaporation											Mean-annual free-water-surface evaporation ranges from approximately 1,500 mm/yr in the northern part of the region to greater than 2,000 mm/yr in the southwestern part.

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
POTENTIAL HOST ROCK											
Granitic rocks											
Total outcrop area, in km^2.	330	210	30	10	30	330	2,310	270	200	130	Granitic rocks occur at shallow depths (less than 300 m) in large portions of SA–01, SA–02, SA–06, SA–07, and SA–08.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	280	180	20	0	20	230	2,220	220	190	120	Unsaturated granitic rocks occur in SA–01, SA–02, SA–03, and SA–07 and occur to limited extent in SA–06, SA–08, and SA–09.
Unsaturated zone more than 150 m thick:											
Basaltic rocks											
Total outcrop area, in km^2.	0	70	140	0	0	10	260	10	40	20	Maximum aggregate basalt thickness is 400 m. Individual flows are 15–20 m thick.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	0	70	120	0	0	10	240	10	20	0	
Tuffaceous rocks											
Total outcrop area, in km^2.	0	0	60	120	0	0	10	20	20	190	Tuffaceous rocks are commonly thin and mixed with other volcanic rocks. In SA–04 and SA–05, mixed volcanic tuff sequences are as thick as 100 m.

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
POTENTIAL HOST ROCK—Continued											
Tuffaceous Rocks—Continued											
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	0	0	60	120	0	0	10	20	20	30	
Argillaceous rocks											Dominantly argillaceous units greater than 150 m in thickness do not occur in the region.
Areas underlain by unsaturated basin fill more than 150 m thick.											
Total outcrop area, in km^2.	0	0	200	0	0	10	390	610	710	360	Unsaturated basin fill as great as 150 m thick occurs in SA–03, SA–07, SA–08, SA–09, and SA–10.
Total outcrop area of potential host rock (does not include unsaturated basin fill).											
Total surface area, in km^2.	330	280	230	130	30	340	2,580	300	260	340	
Total surface area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	280	250	200	120	20	270	2,470	250	230	150	

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
QUATERNARY TECTONIC ACTIVITY											
Strain release											
Strain release of more than 10 occurs in unit.	NO	NO	NO	YES	NO	YES	NO	NO	NO	YES	
Percent of outcrop area of potential host rock within 10 km of areas where strain release is more than 10.	0	0	0	0	0	10	0	0	0	10	
Vertical crustal movement											
Long term											
Movement of more than 4 m per 10^4 yr occurs within unit.	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	
Percent of outcrop area of potential host rock with movement of more than 4 m per 10^4 yr.	0	0	0	0	0	0	0	0	0	0	
Short term											
Vertical crustal movement of more than 4 mm/yr based on geodetic leveling.	NO	NO	NO	YES	NO	YES	NO	NO	NO	NO	
Percent of outcrop area of potential host rock with movement of more than 4 mm/yr based on geodetic leveling.	0	0	0	0	0	10	0	0	0	10	

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
QUATERNARY TECTONIC ACTIVITY—Continued											
Quaternary faults											
Quaternary fault(s) occurs in unit.	YES	YES	NO	NO	NO	YES	YES	YES	YES	YES	Known Quaternary faults are sparse in the region.
Percent of outcrop area of potential host rock within 10 km of Quaternary fault.	10	0	0	0	0	0	10	20	40	10	
Heat flow											
Heat flow more than 2.5 heat flow units occur within ground-water unit.	NO	NO	NO	NO	NO	NO	YES	NO	NO	YES	
Percent of outcrop area of potential host rock within 10 km of area where heat flow is more than 2.5 heat flow units.	0	0	0	0	0	0	10	0	0	0	
Quaternary volcanism											
Quaternary volcanism occurs within unit.	NO	NO	YES	NO	NO	YES	NO	NO	NO	NO	Quaternary volcanism in SA–03 is entirely restricted to areas near ground-water discharge. Quaternary volcanism in SA–06 is minor.

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
QUATERNARY TECTONIC ACTIVITY—Continued											
Heat flow—Continued											
Percent of outcrop area of potential host rock within 10 km of area where Quaternary volcanism has occurred.	0	0	10	0	0	10	0	0	0	0	
GEOMORPHIC PROCESSES											Lowering of the base level of the Colorado River and climatic change during a glacial epoch to pluvial climate may cause entrenchment of trunk streams.

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
GROUND-WATER HYDROLOGY											
Ground-water flow conditions.											
Common values of relative ground-water traveltime near the water table from areas of potential host rock to natural discharge areas.	1–5	1–5	1–10	5–10	1–5	1–10	1–5	1–10	1–5	1–5	Flow paths are difficult to determine and model in SA–07. Unsaturated zones may be more intensive than mapped; gradients may be lower than estimated and travel-times consequently longer than shown. Most large springs occur in SA–07 and SA–09. Springs may shorten flow paths from potential host rock. Areas of thick unsaturated zone may be more extensive than mapped.
Longest relative travel-time near the water table from areas of potential host rock to natural discharge areas.	1–5	5–10	10–20	5–10	1–5	10–20	5–10	5–10	5–10	1–5	
Changes in boundary conditions.											
Part of area inundated by Pleistocene lake.	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
GROUND–WATER HYDROLOGY—Continued											
Changes in boundary conditions—Continued											
Percent of outcrop area of potential host rock inundated by Pleistocene lake.	0	0	0	0	0	0	0	0	0	0	
Ground-water supply											Granitic rocks are minor sources of water supply. Basin-fill deposits and basaltic and tuffaceous rocks may yield moderate to large quantities of water. Ground-water withdrawal in the northern part of SA–03 and southern part of SA–07 has caused major depressions in the water table in those areas.
GEOCHEMISTRY											
Water quality											
Area, in km^2, of basin fill where ground water contains dissolved-solids concentration of:											
Less than 500 mg/L	1,550	1,550	1,750	1,050	1,000	3,050	2,800	1,450	1,750	750	
500–1,000 mg/L	100	50	450	50	50	750	200	50	100	50	
1,000–3,000 mg/L	150	100	50	50	50	450	0	0	50	200	
3,000–10,000 mg/L	100	100	100	150	0	0	0	0	0	0	
More than 10,000 mg/L.	0	0	0	0	0	0	0	0	0	0	

TABLE 5.—*Summary of geologic and hydrologic characteristics of the Sonoran region, Arizona*—Continued

Characteristic	Ground-water unit										Comments
	SA–01	SA–02	SA–03	SA–04	SA–05	SA–06	SA–07	SA–08	SA–09	SA–10	
GEOCHEMISTRY—Continued											
Retardation of radionuclides											Deep flow paths commonly flow through fine-grained basin fill or crystalline (granitic or metamorphic) rocks which offer radionuclide retardation.
MINERAL AND ENERGY RESOURCES											
Percent of potential-host-rock outcrop area coincident with mapped mineral resource area.	0	3	4	0	0	12	4	7	4	0	Numerous small inactive prospects in SA–06 within granitic host rock areas.
											Active openpit copper mine in SA–03. More than $1.5 billion produced (Ajo district).
											Active openpit copper mine in SA–07 More than $100 million produced (Eureka district).
											Active base and precious metal mines in SA–08, and SA–09. More than $100 million produced (Wallapai district).
											Several metallic mineral districts have been reopened intermittently.
											No coal occurrences or productive oil or gas wells.

TABLE 6.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Sonoran region, Arizona*

[m, meter; yr, year; mg/L, milligram per liter]

Potentially favorable hydrogeologic factors	Issues of concern and study needs
POTENTIAL HOST ROCKS	
Some granitic rocks are massive and unfractured. Granitic rocks are widespread and underlie large areas within repository depths outside surface-outcrop areas.	Locally granitic rocks are highly fractured and foliated.
Basaltic rocks in thick, unsaturated zones are widespread. Aggregate thicknesses are as great as 400 m.	Individual flows are 15–20 m thick, composing a nonhomogeneous mass.
Tuffaceous rocks in thick, unsaturated zones occur in significantly large areas. Unsaturated basin fill as thick as 150 m occurs in the region.	Thin beds of tuffaceous and other volcanic rocks compose a nonhomogeneous mass.
QUATERNARY TECTONIC ACTIVITY	
Most units have strain release of less than 10.	Some areas have strain release of more than 10.
Vertical crustal movement generally is less than 2 m per 10^4 yr.	Vertical crustal movement is more than 4 m per 10^4 yr in parts of three units due to nearby tectonic forces.
Quaternary faults are sparse and largely located in basin areas.	Quaternary faults have been mapped in most units; but detailed studies have not been made.
Geothermal heat flow is less than 2.5 heat flow units in most of the region.	Locally geothermal heat flow is more than 2.5 heat flow units in groundwater units SA–07 and SA–10.
Quaternary volcanic activity is absent in most of the region.	Quaternary volcanic activity is within 10 km of potential host rocks in groundwater units SA-03 and SA–06.
GEOMORPHIC PROCESSES	
Denudation at a maximum rate equal to the long-term rate of vertical crustal movement, 2-4 m per 10^4 yr, over most of the area would not reduce effectiveness of a waste-isolation environment at a depth as shallow as 300 m over a period of 100,000 yr.	Long-term vertical crustal movement as great as 4 m per 10^4 yr could indicate adverse tectonic activity.
GROUND-WATER HYDROLOGY	
Ground-water flow conditions	
Relative ground-water traveltimes of from potential host rocks to natural discharge areas are very long.	Site data on hydrologic properties rocks and hydraulic gradients are sparse.
Changes in boundary conditions	
Lowering of base level in trunk streams will tend to attenuate rise in water level during a glacial epoch and maintain unsaturated section.	Increase in recharge during a pluvial cycle will tend to decrease area of potential host rocks in the unsaturated zone.

TABLE 6.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Sonoran region, Arizona*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GROUND-WATER HYDROLOGY—Continued	
Changes in boundary conditions—Continued	
	Change to pluvial climate will tend to increase hydraulic gradient and decrease traveltime near the water table. Increase in hydraulic gradients will decrease ground-water traveltime.
Water supply	
Granitic rocks are minor sources of water supply.	Basin-fill deposits and basaltic and tuffaceous rocks may yield moderate large quantities of water.
	Ground-water withdrawal in ground-water unit SC–07 has caused depressions in the water table in those areas.
GEOCHEMISTRY	
Water quality	
Ground water contains more than 3,000 mg/L dissolved solids in parts of ground-water units SA–02, SA–03, and SA–04.	Ground-water quality is less than 3,000 mg/L dissolved solids over most of the region.
Retardation of radionuclides	
Deep flow paths commonly flow through fine-grained basin fill or crystalline (granitic or metamorphic) rocks which offer radionuclide retardation.	
MINERAL AND ENERGY RESOURCES	
The few active mines affect only a small part of the region.	Active mines are in ground-water units SA–03, SA–07, SA–08, and SA–09.
Potential for geothermal energy is low.	Thermal ground water locally may have potential for space heating.
	Mineral potential is poorly known.

activity and some short-term crustal uplift. A Quaternary basalt flow crops out in the northeastern part of ground-water unit SA–03. Tectonism is interpreted to be of minor concern in assessment of repository environments in the southern part of the Sonoran region, Arizona. Tectonic stability and the mature geomorphic development of the region indicate that erosion should not impair the integrity of a repository at a depth of 300 m over a period of 100,000 yr.

Structurally, the basement rocks of the region have been complexly foliated and faulted during several episodes of tectonism. Evidence of control of ground water by fault planes is given by the few thermal springs. The geologic age of the faults—even the basin-and-range extension faults are relatively old—and the relatively small volumetric flux through the flow systems would support the view that the fault zones are of low permeability.

Ground-water potential from the crystalline metamorphic and igneous rocks is small, although the water quality is good. Ground-water potential is moderate to large in volcanic rocks and coarse-grained basin fill, and the water quality is good in these units, except in the discharge area along the Gila and Colorado Rivers.

CONCLUSIONS

The principal favorable factors for waste isolation in the Sonoran region, Arizona, include the arid environment; potential host media in saturated and unsaturated intrusive rocks, saturated salt, and unsaturated extrusive rocks; long ground-water traveltimes; and low Quaternary tectonic activity. Estimated traveltimes are very long (more than 100,000 yr) under present climatic conditions and would probably be of similar lengths under pluvial conditions such as existed in the Pleistocene. Chemical retardation of radionuclides would be afforded by sorption by clay minerals in the weathered igneous and metamorphic rocks and in zeolitic and argillaceous basin-fill deposits. Ground-water quality is generally good, except where associated with evaporite deposits, as in ground-water unit SA–09. Ground- water development in bedrock will be restricted because of the low yield potential. The more favorable areas for further study appear to be ground-water units SA–01, SA–02, SA–03, SA–04, SA–08, and SA–09.

The areas which appear to have less favorable environments at this level of screening are ground-water units SA–05, SA–07, and SA–10. Ground-water units SA–05 and SA–10 lack large areas of potential host rock. Although ground-water unit SA–07 has abundant potential host rock, it generally has very short, interrupted flow paths. Deeper flow paths would be difficult to model, and the analyses would have a very high degree of uncertainty.

SONORAN REGION, CALIFORNIA

SUMMARY OF GEOLOGIC AND HYDROLOGIC FACTORS

The Sonoran region of California has an area of about 21,600 km^2 and is located west of and adjacent to the Colorado River (fig. 5). The geologic and hydrologic characteristics of the region are summarized in table 7. The potentially favorable hydrogeologic factors for waste isolation and corresponding issues of concern for each factor are given in table 8.

HYDROGEOLOGIC ENVIRONMENTS

Hydrogeologic environments typical of the Sonoran region, California, are discussed below and may be prospective for further study. Data are not available for assessment of specific sites as isolation environments for high-level radioactive waste. Therefore, specific sites in the region are not identified. However, the hydrogeologic environments that are described are generally similar to some which do occur in the region.

Hydrogeologic environments for waste isolation in the region are shown in sections in plate 1. Prospective host rocks are primarily saturated and unsaturated granitic intrusive bodies and unsaturated basin fill. Hydrogeologic section SC–A (pl. 1) shows younger igneous rocks intruding Precambrian metamorphic rocks; these rocks were complexly thrust faulted prior to basin-and-range extensional faulting. Basins adjacent to the Colorado River have open drainage or are partly closed by low topographic divides, such as at Danby Lake and Ford Dry Lake. Hydrogeologic section SC–B (pl. 1) depicts Precambrian metamorphic rocks also cut by younger granitic intrusive bodies. These crystalline rocks are unconformably overlain by Tertiary volcanic rocks, Quaternary and Tertiary continental deposits, and Quaternary alluvial, lacustrine, and fluvial deposits. Ground-water basins in ground-water units SC–05 and SC–06 are topographically closed.

The climate is arid. Most of the area receives less than 100 mm/yr of precipitation, about half of which falls as convective thundershowers during the summer when potential evaporation is great. A few of the high mountain ranges receive as much as 200 mm/yr. Recharge is very small and probably occurs intermittently in response to large storm events.

Potential environments for high-level waste storage in igneous plutons in the mountain ranges include both the unsaturated and saturated zones in which ground-water flux is small.

There are two scenarios for the natural termination of flow paths in this region. Discharge either occurs in closed basins such as Danby and Cadiz Lakes or at the Colorado River. The long head of deep flow paths may be

TABLE 7.—*Summary of geologic and hydrologic characteristics of the Sonoran region, California*

[km^2, square kilometer; m, meter; mm/yr, millimeter per year; <, less than; mg/L, milligram per liter]

Characteristic	Ground-water unit						Comments
	SC–01	SC–02	SC–03	SC–04	SC–05	SC–06	
PHYSIOGRAPHY							
Area, in km^2	1,800	4,500	5,300	1,900	5,500	2,600	Altitudes of the basins in the region commonly are 150–750 m. The range blocks are greater than 1,500 m in some places but commonly are 900–1,200 m high.
Area of basin fill, in km^2	1,000	1,680	3,250	1,000	3,100	1,400	
Precipitation							Precipitation in most of the area is less than 100 mm/yr; only part of the area has precipitation greater than 200 mm/yr.
Evaporation							Mean annual free-water-surface evaporation generally ranges from 1,750 to greater than 2,000 mm/yr.
POTENTIAL HOST ROCK							
Granitic rocks							
Total outcrop area, in km^2	50	450	470	190	680	360	Granitic rocks are widespread and occur in large outcrop areas.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	30	420	430	170	650	330	Both saturated and unsaturated potential environments exist in crystalline rocks.
Unsaturated zone more than 150 m thick:							
Basaltic rocks							
Total outcrop area, in km^2	0	0	20	20	0	0	Basaltic rocks are scattered through all the units in the region. They range in thickness from 60 to 125 m and occur in areas of thick, unsaturated zones in SC–03, SC–04, and SC–05. They are mostly vesicular, olivine basalts commonly interbedded with volcaniclastic rocks.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	0	0	10	10	0	0	
Tuffaceous rocks							Tuffaceous rocks occur in SC–01 and SC–02 but have an insufficient thickness of unsaturated zone to be considered as potential host rock. Tuffs are as thick as 350 m in the southeastern part of SC–01
Total outcrop area, in km^2	0	0	0	0	0	0	

TABLE 7.—*Summary of geologic and hydrologic characteristics of the Sonoran region, California*—Continued

Characteristic	Ground-water unit						Comments
	SC–01	SC–02	SC–03	SC–04	SC–05	SC–06	
POTENTIAL HOST ROCK—Continued							
Tuffaceous rocks—Continued							
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	0	0	0	0	0	0	
Argillaceous rocks							Dominantly argillaceous units greater than 150 m in thickness do not occur in the region.
Areas underlain by unsaturated basin fill more than 150 m thick.							
Total ourcrop area, in km^2	0	40	710	130	100	400	
Total outcrop area of potential host rock (does not include unsaturated basin fill).							
Total surface area, in km^2	50	450	490	210	680	360	
Total surface area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	30	420	450	180	650	330	
QUATERNARY TECTONIC ACTIVITY							
Strain release							
Strain release more than 10 occurs in unit.	YES	YES	NO	NO	YES	NO	
Percent of outcrop area of potential host rock within 10 km of strain release more than 10.	10	30	0	0	10	0	Granitic host rocks in the western part of SC–02 (approximately 30 percent of the potential host rocks) are within 10 km of an area of strain release of more than 10. Minor parts of SC–01 and SC–05 are within 10 km of an area of strain release of more than 10.
Vertical crustal movement							
Long term							
Movement of more than 4 m per 10^4 yr occurs within unit.	YES	YES	NO	NO	YES	NO	
Percent of outcrop area of potential host rock with movement of more than 4 m per 10^4 yr.	90	50	0	0	25	0	

TABLE 7.—*Summary of geologic and hydrologic characteristics of the Sonoran region, California*—Continued

Characteristic	Ground-water unit SC–01	SC–02	SC–03	SC–04	SC–05	SC–06	Comments
QUATERNARY TECTONIC ACTIVITY—Continued							
Vertical crustal movement—Continued							
Short term							
Movement of more than 4 mm/yr based on geodetic leveling.	YES	YES	YES	NO	YES	NO	All of SC–01 and SC–02 and parts of SC–03 and SC–05 are in areas of crustal movement of greater than 4 mm/yr based on geodetic leveling.
Percent of outcrop area of potential host rock with movement of more than 4 mm/yr based on geodetic leveling.	100	100	30	0	20	0	
Quaternary faults							
Quaternary fault(s) occurs in unit.	YES	YES	YES	NO	YES	YES	
Percent of outcrop area of potential host rock within 10 km of Quaternary fault.	10	50	10	0	10	10	
Heat flow							
Heat flow more than 2.5 heat flow units occurs within unit.	NO	YES	NO	NO	YES	NO	
Percent of outcrop area of potential host rock within 10 km of heat flow more than 2.5 heat flow units.	0	20	0	0	10	0	
Quaternary volcanism							
Quaternary volcanism occurs within unit.	NO	NO	YES	YES	YES	YES	Only SC–06 has significant known amounts of Quaternary volcanism located in areas within 10 km of potential host rock.
Percent of outcrop area of potential host rock within 10 km of Quaternary volcanism.	0	0	10	10	10	50	

TABLE 7.—*Summary of geologic and hydrologic characteristics of the Sonoran region, California*—Continued

Characteristic	Ground-water unit						Comments
	SC–01	SC–02	SC–03	SC–04	SC–05	SC–06	
GEOMORPHIC PROCESSES							Lowering of the base level of the Colorado River and climatic change during a glacial epoch to pluvial climate may cause entrenchment of trunk streams.
GROUND-WATER HYDROLOGY							
Ground-water flow conditions							
Common values of relative ground-water traveltime near the water table from areas of potential host rock to natural discharge areas.	1–5	1–5	1–5	1–5	1–5	1–5	No large springs are reported in the region. A few warm springs with low flows occur in SC–02, SC–05, and SC–06. All ground-water flow in SC–05 and SC–06 and part of the ground-water flow in SC–03 are contained within closed basins.
Longest relative travel-time near the water table from areas of potential host rock to natural discharge areas.	1–5	1–5	1–5	1–5	1–5	1–5	
Changes in boundary conditions.							
Part of area inundated by Pleistocene lake.	NO	NO	YES	NO	YES	YES	
Percent of outcrop area of potential host rock inundated by Pleistocene lake.	0	0	0	0	<1	3	
Ground-water supply							Basin-fill deposits, basaltic and tuffaceous rocks, and sandstones may yield small to moderate quantities of water. Basin fill locally yields large quantities of water.
							Ground-water withdrawal in SC–06 has caused a depression in the water table.

TABLE 7.—*Summary of geologic and hydrologic characteristics of the Sonoran region, California*—Continued

Characteristic	Ground-water unit						Comments
	SC–01	SC–02	SC–03	SC–04	SC–05	SC–06	
GEOCHEMISTRY							
Water quality							
Area, in km^2, of basin fill containing dissolved-solids content of:							Ground water generally contains less than 1,000 mg/L dissolved solids in most of the basin fill.
Less than 500 mg/L	850	130	1,550	650	2,200	800	
500–1,000 mg/L	100	600	1,150	250	300	250	
1,000–3,000 mg/L	50	750	350	100	200	250	
3,000–10,000 mg/L	0	200	100	0	100	100	
More than 10,000 mg/L	0	0	100	0	300	0	
Retardation of radionuclides							Most deep flow paths are through dense crystalline rocks (granitic or metamorphic rocks) and fine-grained alluvium which may offer radionuclide retardation.
MINERAL AND ENERGY RESOURCES							
Percent of potential-host-rock outcrops area coincident with mineral resource area.	0	44	16	5	35	22	Numerous lode-gold deposits have produced small tonnages of ore. Base-metal production generally is small.
							Large gypsum resources occur in Riverside County (SC–02); none are currently productive.
							Salt and calcium chloride have been produced from Bristol, Cadiz (SC–05), and Danby (SC–03) Lakes.
							Most of the productive mines and mineralized areas are of limited extent.
							No coal occurrences or productive oil or gas wells are identified in the region.

intersected by mined repositories in the unsaturated and saturated zones. Flow paths in crystalline igneous and metamorphic rocks project beneath the basin fill which presents barriers to upward flow by its indurated nature. The lower part of the basin fill, composed of continental subaerial and lake deposits, or the marine Bouse Formation in basins near the Colorado River may have the lowest permeability of rocks in the flow system. Clay weathering products in joint planes of crystalline metamorphic and volcanic rocks in basin fill will also retard radionuclide transport. Ground-water travel is under low hydraulic gradient in rocks of low permeability in long flow paths. There are no large thermal springs in the area that would indicate highly permeable fault zones and permit rapid ground-water movement from great depths to the surface. Ground-water velocities at depths greater than 300 m in the metamorphic and igneous intrusive rocks, having a K/ϕ (ratio of hydraulic conductivity to effective porosity) from 5×10^{-4} to 2×0^{-2} m/d, under a hydraulic gradient of 0.03, would range from 1.5×10^{-5} to 6×10^{-4} m/d. Projected ground-water traveltimes along deep flow paths in crystalline igneous and metamorphic rocks under a gradient of 0.003 indicate that traveltimes from near ground-water divides to natural discharge areas would be much greater than 100,000 yr.

Ground-water velocity is also a function of flux and moisture content. In the unsaturated zone, moisture content is less than porosity. Velocities could be as great as 6×10^{-3} m/d for a downward flux of 10 mm/yr and a moisture content of 0.5 percent (possible in basalt) and less than 6×10^{-5} m/d for downward flux of 0.1 mm/yr and a moisture content of 5 percent (possible in basin fill). Based on these assumptions, the traveltime of water through a 200-m thickness of unsaturated zone could be as low as 100 yr for basalt and as great as 100,000 yr for basin fill.

The unsaturated basin fill is possibly of sufficient thickness to host a mined repository. An important advantage of a potential site in the unsaturated zone would be a location in which the saturated flow beneath the repository moves into the crystalline rock beneath the basin fill.

Tectonically the area is generally stable. Siting studies should assess the specific hazards associated with nearby Quaternary faults and volcanism. The tectonic stability and mature geomorphic development of the region indicate that erosion should not impair the integrity of a repository at a depth of 300 m over a period of 100,000 yr or more.

Ground-water potential in the crystalline rocks and fine-grained lower part of the basin fill is low, reducing the chance of inadvertent human intrusion in the deep, long flow paths. Mineral and energy potential is not presently exploited.

CONCLUSIONS

Prospective host media for isolation of high-level radioactive waste in the Sonoran region, California, are primarily igneous intrusive rocks and unsaturated basin fill where traveltimes of ground water to discharge areas are very long. The environments are enhanced by the arid climate in which potential evaporation greatly exceeds precipitation, the lack of large or thermal springs indicative of anomalous ground-water flow, and the tectonic stability of the region. Ground-water traveltimes are projected, under both present and pluvial conditions, to be greatly in excess of 100,000 yr from many potential-host-rock areas to discharge areas. Recurrence of pluvial conditions would tend to increase ground-water levels and reduce the thickness and extent of the unsaturated zone. Chemical retardation of radionuclides will be afforded by clay minerals in both weathered crystalline rocks and basin fill. Hydraulic barriers in the lower part of the basin fill would result from the fine-grained and indurated nature of the sediments.

Long flow paths from potential host rock and unsaturated areas to discharge areas appear most favorable in ground-water units SC–02, SC–03, SC–04, SC–05, and SC–06. Though the region is complex geologically, the absence of hydrologic anomalies lends confidence to estimates of long traveltimes projected from host rocks to natural discharge areas. Tectonically the region is stable, but the long-term vertical uplift rate in the western parts of ground-water units SA–01, SA–02, SA–05, and SA–06 needs to be evaluated in further studies.

DEATH VALLEY REGION, NEVADA AND CALIFORNIA

SUMMARY OF GEOLOGIC AND HYDROLOGIC FACTORS

The Death Valley region has an area of about 80,200 km^2 in south-central Nevada and southern California (pl. 6). The region is named for the largest and most prominent desert basin in the region, Death Valley, which is the ground-water discharge area for a large part of the region. The geologic and hydrologic characteristics of the region are summarized in table 9. For each factor considered in the regional phase of screening, the potentially favorable factors for waste isolation and the corresponding issues of concern are given in table 10.

TABLE 8.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Sonoran region, California*

[mm/yr, millimeter per year; m, meter; km, kilometer; mg/L, milligram per liter]

Potentially favorable hydrogeologic factors	Issues of concern and study needs
PHYSIOGRAPHY	
Precipitation is extremely low throughout the region, between 100 and 200 mm/yr with very few exceptions.	
Mean-annual free-water-surface evaporation ranges from 1,750 to more than 2,000 mm/yr.	
POTENTIAL HOST ROCKS	
Granitic-rock outcrops are abundant throughout most of the area.	
Many sheared granitic rocks occur in thick unsaturated areas.	Much of the granitic rock in the region is reported to be tectonically fractured and sheared.
Fractures in some granitic rocks may have been "healed" by remelting.	
Tuffaceous rocks are widespread but generally thin in ground-water units SC–01 and SC–02. However ash-flow tuffs are as much as 350 m thick in the southeastern part of ground-water unit SC–01.	
Large areas of unsaturated basin fill occur in ground-water units SC–03 through SC–06.	
QUATERNARY TECTONIC ACTIVITY	
Most parts of ground-water units SC–03 SC–04, SC–05, and SC–06 have long-term vertical crustal movement of less than vertical crustal movement of 4 m per 10^4 yr.	All parts of ground-water units SC–01 and SC–02 have long-term vertical crustal movement of more than 4 m per 10^4 yr.
	Granitic host rocks in western part of ground-water unit SC–02 (approximately 30 percent of potential host rocks) are within 10 km of an area of strain release greater than 10. Minor parts of ground-water units SC–01 and SC–05 are affected.
Quaternary faults are sparsely located in ground-water units SC–01, SC–02, SC–03, SC–05, and SC–06 and have not been mapped in ground-water unit SC–04.	Quaternary faults are within 10 km of host rock (approximately 50 percent of the host rock) in ground-water unit SC–02.
Geothermal heat flow is less than 2.5 heat flow units in most of the region.	Locally geothermal heat flow is greater than 2.5 heat flow units in ground-water units SC–02 and SC–04.
Quaternary volcanic activity is absent or insignificant in most of the region.	Quaternary volcanic activity is within 10 km of potential host rock (approximately 50 percent of the host rock) in ground-water unit SC–06.

TABLE 8.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Sonoran region, California*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GEOMORPHIC PROCESSES	
Most parts of ground-water units SC–03, SC–04, SC–05, and SC–06 have long-term crustal movement of less than 4 m per 10^4 yr. Denudation of the surface at a maximum rate of 1–4 m per 10^4 yr would not reduce effectiveness of a waste-isolation environment at a depth of as shallow as 300 m over a period of 100,000 yr.	Long-term vertical crustal movement as great as 4 m per 10^4 yr in the western half of ground-water unit SC–01, the western half of ground-water unit SC–02, and the southwestern portion of ground-water unit SC–05 may indicate adverse tectonic activity.
	Short-term local uplift of more than 4 mm/yr occurs in all parts of ground-water units SC–01 and SC–02 and in the southern parts of ground-water units SC–03 and SC–05.
GROUND-WATER HYDROLOGY	
Ground-water flow conditions	
Very long ground-water traveltimes occur in deep sections from potential host rocks to natural discharge areas.	Subsurface data on hydrologic properties of rocks and hydraulic gradients are sparse.
	Relative traveltimes near the water table from areas of potential host rock to natural discharge areas are short.
All ground-water flow in ground-water units SC–05 and SC–06 and part of the ground-water flow in ground-water unit SC–03 are contained within closed basins, offering containment within one basin.	Containment within one basin precludes dilution at discharge areas.
Fine-grained deposits in the lower parts of basin fill are barriers to ground-water flow.	Argillaceous confining beds of great thickness and areal extent generally are not present in the mountain blocks or beneath the basin fill.
Changes in boundary conditions	
Entrenchment of the Colorado River, due to lowering of its base level and a change to a pluvial climate, will tend to attenuate change in water level due to increase in recharge.	Increase in ground-water level during pluvial cycle will decrease area of potential host rock in the unsaturated zone and increase ground-water velocity.
Water supply	
Granitic rocks, the primary potential host rocks in this region, are minor sources of water supply.	Basin-fill deposits may yield moderate to large quantities of usable water.
	Ground-water withdrawal in ground-water unit SC–06 has caused a depression in the water table.

TABLE 8.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Sonoran region, California*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GEOCHEMISTRY	
Water quality	
Discharge areas in ground-water units SC–05 and SC–06 and one discharge area in ground-water unit SC–03 have dissolved-solids concentration greater than 3,000 mg/L.	Ground water generally contains less than 3,000 mg/L dissolved solids.
Retardation of radionuclides	
Most deep flow paths are through dense crystalline rocks (granitic or metamorphic rocks) and fine-grained alluvium which may offer radionuclide retardation.	
MINERAL AND ENERGY RESOURCES	
Most of the productive mines and mineralized areas are of limited extent.	Numerous lode-gold deposits have produced small tonnages of ore.
Base-metal production is generally small.	
Gypsum is produced primarily for local markets. No gypsum mines are currently productive.	Large gypsum resources occur in Riverside County (ground-water unit SC–02).
	Salt has been produced from Bristol, Cadiz (ground-water unit SC–05), and Danby (ground-water unit SC–03) Lakes.
No coal occurrences or productive oil or gas wells are identified in the region.	

HYDROGEOLOGIC ENVIRONMENTS

Potential host rocks shown in the hydrogeologic sections in plate 1 include saturated and unsaturated igneous intrusive rocks and some small outcrops of unsaturated basalt. Hydrogeologic environments typical of those occurring in ground-water unit DV–03 are shown in section DV–A (pl. 1). The environments are characterized by geologic terrane dominated by thick Paleozoic carbonate rocks which allow ground-water to underdrain much of the area. The Paleozoic carbonate rocks overlie thick fine-grained clastic rocks of Cambrian and Precambrian age and Precambrian metamorphic rocks. The whole sequence is intruded by Cretaceous igneous rocks. Tertiary volcanic rocks and clastic basin fill occupy the block-faulted basins formed during basin-and-range crustal extension.

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California*

[km², square kilometer; m, meter; mm/yr, millimeter per year; <, less than; mg/L, milligram per liter]

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
PHYSIOGRAPHY										
Area, in km²	9,000	1,300	44,400	4,700	2,100	2,200	7,700	3,500	5,300	The altitudes in the Death Valley region range from more than 86 m below sea level in Death Valley to more than 3,000 m above sea level. Altitudes of the basins are generally below 150 m, whereas mountains are generally above 2,400 m.
Area of basin fill, in km²	4,300	450	14,350	1,500	450	50	2,900	1,000	2,800	
Precipitation										Precipitation in the region is 100–200 mm/yr with very few exceptions. The western part of DV–06 and the western part of DV–08 are over 250 mm/yr; one small part of DV–03 is over 500 mm/yr.
Evaporation										Mean-annual free-water-surface evaporation for the area ranges from 1,250 to greater than 2,000 mm/yr.
POTENTIAL HOST ROCK										
Granitic rocks										
Total outcrop area, in km²	890	20	1,720	690	440	400	160	600	110	Unsaturated granitic rocks occur in all ground-water units except DV–02.
Total area, in km², of contiguous outcrops that are more than 6.5 km².	840	20	1,590	670	430	400	110	580	100	
Unsaturated zone equal to or greater than 150 m thick:										

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California* —Continued

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
POTENTIAL HOST ROCK—Continued										
Basaltic rocks										
Total outcrop area, in km^2	360	0	290	40	20	0	60	20	10	Thick, unsaturated basalts occur in DV–01, DV–03, and DV–07.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	350	0	220	40	10	0	50	10	10	
Tuffaceous rocks										
Total outcrop area, in km^2	20	0	3,680	0	0	0	640	50	340	Thick, unsaturated tuffs occur in DV–01, DV–03, DV–07, DV–08, and DV–09. Aggregate thickness is as much as 4,100 m. Unsaturated thickness of tuffs in DV–03 approaches 700 m.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	10	0	3,470	0	0	0	620	40	330	
Argillaceous rocks										
Total outcrop area, in km^2	0	10	950	30	80	110	30	0	80	Argillaceous rocks occur in DV–02, DV–03, DV–04, DV–05, DV–06, DV–07, and DV–09.
Total area of contiguous outcrops that are more than 6.5 km^2.	0	0	880	30	20	60	20	0	80	
Areas underlain by unsaturated basin fill more than 150 m thick.										
Total outcrop area, in km^2	710	40	3,850	30	0	0	60	40	0	Very thick, unsaturated basin fill occurs in DV–03.

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California*—Continued

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
POTENTIAL HOST ROCK—Continued										
Total outcrop area of potential host rock (does not include shales or unsaturated basin fill).										
Total surface area, in km^2	1,270	20	5,690	730	460	400	860	670	460	
Total surface area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	1,200	20	5,280	710	440	400	780	630	440	
QUATERNARY TECTONIC ACTIVITY										
Strain release										
Strain release greater than 10.	YES	NO	YES	NO	YES	YES	YES	YES	YES	Earthquakes: DV–06 contains three events of 5–6 magnitude, and one event of 6–7 magnitude; DV–08, two events of 5–6 magnitude and two events of 6–7 magnitude; DV–09, two events of 5–6 magnitude. Many of lesser magnitude also occur. Strain release greater than 100 occurs in DV–03. Earthquakes at Lake Mead are partly related to water impoundment. Earthquakes at the Nevada Test Site are caused in large part by nuclear tests.
Percent of outcrop area of potential host rock within 10 km of strain release greater than 10.	20	0	50	0	0	40	10	50	20	

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California*—Continued

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
QUATERNARY TECTONIC ACTIVITY—Continued										
Vertical crustal movement										
Long term										
Uplift of greater than 4 m per 10^4 yr occurs within unit.	YES	NO	YES	YES	YES	YES	YES	YES	YES	Uplift of more than 20 m per 10,000 yr is indicated by geologic studies in the western parts of units DV–03, DV–04, DV–05, DV–06, and DV–08.
Percent of outcrop area of potential host rock with uplift of more than 4 m per 10^4 yr.	10	0	30	40	50	50	10	100	20	
Short term:										
Movement of more than 4 mm/yr based on geodetic leveling.	NO	NO	NO	NO	NO	NO	NO	NO	NO	
Percent of outcrop area of potential host rock with movement of more than 4 mm/yr based on geodetic leveling.	0	0	0	0	0	0	0	0	0	
Quaternary faults										
Quaternary fault(s) occurs in unit.	YES	YES	YES	YES	YES	YES	YES	YES	YES	
Percent of outcrop area of potential host rock within 10 km of Quaternary fault.	20	100	50	80	80	30	20	60	20	

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California*—Continued

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
QUATERNARY TECTONIC ACTIVITY—Continued										
Heat flow										
Heat flow more than 2.5 heat flow units occurs within unit.	NO	NO	YES	NO	YES	NO	NO	NO	NO	
Percent of outcrop area of potential host rock within 10 km of heat flow more than 2.5 heat flow units.	0	0	0	0	30	0	0	0	0	
Quaternary volcanism										
Quaternary volcanism occurs within unit.	NO	NO	YES	YES	NO	YES	NO	YES	NO	Quaternary volcanism mainly has occurred along southern and western margins of region and in the central part of DV–03.
Percent of outcrop area of potential host rock within 10 km of Quaternary volcanism.	0	0	10	40	0	0	0	80	0	
GEOMORPHIC PROCESSES										Lowering of base level of Colorado River and climatic change may cause entrenchment of trunk streams.
GROUND–WATER HYDROLOGY										
Ground-water flow conditions										
Common values of relative ground-water traveltime near the water table from areas of potential host rock to natural discharge areas.	0–1	0–1	1–5	1–5	1–5	1–5	1–5	5–10	1–10	Numerous springs occur in the region; most are located at major ground-water discharge areas. Locally, large springs may substantially shorten flow paths.

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California*—Continued

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
GROUND-WATER HYDROLOGY—Continued										
Ground-water flow conditions—Continued										Many short (1–5) traveltimes in DV–03 are due to flow in the basin fill. Traveltimes from these basins through underlying aquifers to natural discharge areas may be appreciable.
Longest relative traveltime near the water table from areas of potential host rock to natural discharge areas.	1–5	0–1	20–50	5–10	1–5	5–10	5–10	5–10	10–20	
Changes in boundary conditions										
Part of area inundated by Pleistocene lake.	NO	YES	YES	YES	YES	NO	YES	YES	YES	
Percent of outcrop area of potential host rock inundated by Pleistocene lake.	0	0	<1	2	0	0	0	2	0	
Ground-water supply										Basin fill, basaltic and tuffaceous rocks, sandstone, and carbonate rocks may yield small to moderate quantities of water. Large quantities of water are available locally.

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California*—Continued

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
GROUND–WATER HYDROLOGY—Continued										
Ground–Water Supply—Continued										Ground-water withdrawal near Las Vegas in DV–01 and in Pahrump Valley in DV–03 has caused depressions in the water table.
GEOCHEMISTRY										
Water quality										
Area, in km^2, of basin fill containing dissolved-solids content of:										
Less than 500 mg/L	2,200	300	8,450	1,000	300	50	2,100	650	2,200	
500–1,000 mg/L	1,750	100	3,050	400	100	0	400	150	300	
1,000-3,000 mg/L	300	50	2,350	100	40	0	300	100	150	
More than 3,000 mg/L.	50	0	500	0	10	0	100	100	150	
Retardation of radionuclides.										Deep flow paths are through a variety of rock types, which present a complex environment for determining radionuclide retardation properties.

TABLE 9.—*Summary of geologic and hydrologic characteristics of the Death Valley region, Nevada and California*—Continued

Characteristic	Ground-water unit									Comments
	DV–01	DV–02	DV–03	DV–04	DV–05	DV–06	DV–07	DV–08	DV–09	
MINERAL AND ENERGY RESOURCES										
Percent of potential-host-rock outcrop area coincident with mineral resource area.	22	0	3	6	17	0	35	3	15	Historically, this region has produced substantial amounts of mineral commodities. Mountain Pass district (southwestern part of DV–01) contains an important world source of rare-earth elements. Magnesite and brucite currently are mined near Gabbs (DV–09). Molybdenum currently is being mined in the west-central part of DV–07. Silver Peak Marsh (Clayton Valley) (southwestern part of DV–07) contains an important world source of lithium. There are no productive coal deposits or oil and gas wells in the region. Two KGRA's are present: Saline Valley (central part of DV–05), and Silver Peak (southwestern part of DV–07).

TABLE 10.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Death Valley region, Nevada and California*

[mm/yr, millimeter per year; m, meter; km, kilometer; yr, year; mg/L milligram per liter]

Potentially favorable hydrogeologic factors	Issues of concern and study needs
PHYSIOGRAPHY	
Precipitation is extremely low throughout the region, 100–200 mm/yr, with very few exceptions.	The western parts of ground-water units DV–06 and DV–08 have precipitation over 250 mm/yr; a small part of ground-water unit DV–03 has precipitation over 500 mm/yr.
Mean-annual free-water-surface evaporation ranges from 1,250 to more than 2,000 mm/yr, greatly exceeding precipitation.	
POTENTIAL HOST ROCKS	
Numerous granitic rocks occur throughout most of the region.	Carbonate rocks containing potable water may underlie basalt, tuff, and basin fill in most of the region, particularly in ground-water unit DV–03.
Numerous thick, unsaturated basalts occur in ground-water units DV–01, DV–03, and DV–07.	
Numerous thick, unsaturated tuffs occur in ground-water units DV–03, DV–07, and DV–09. Large areas of thick, unsaturated basin fill occur in ground-water units DV–01 and DV–03.	
QUATERNARY TECTONIC ACTIVITY	
Strain release less than 10 at Lake Mead area (ground-water unit DV–01) and Nevada Test Site (ground-water unit DV–02) is partly man-induced.	Strain release less than 10 occurs in all ground-water units except DV–02 and DV–04. Vertical crustal movement is more than 20 m per 10,000 yr as indicated by geologic studies in ground-water units DV–04, DV–05, DV–06, DV–08, and in the western part of ground-water unit DV–03.
	Long-term vertical crustal movement greater than 4 m per 10^4 yr could indicate adverse tectonic activity.
	Quaternary faults occur in every unit in the region.
Geothermal heat flow is less than 2.5 heat flow units in most of the region.	Heat flow is greater than 2.5 heat flow units in ground-water units DV–03 and DV–05, and potentially affects 30 percent of the host rock in ground-water unit DV–05.
Quaternary volcanism is restricted to the western and southern margin of the region and to the central part of ground-water unit DV–03.	Quaternary volcanism is within 10 km of potential host rock areas in ground-water units DV–03, DV–04, DV–06, and DV–08. It affects 40 percent of the potential host rock in ground-water unit DV–04 and 80 percent of the potential host rock in ground-water unit DV–08.

TABLE 10.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Death Valley region, Nevada and California*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GEOMORPHIC PROCESSES	
Denudation at a maximum rate equal to long-term vertical crustal movement of 2–4 m per 10^4 yr over most of the area would not reduce the effectiveness of a waste-isolation environment at a depth as shallow as 300 m over a period of 100,000 yr.	
GROUND-WATER HYDROLOGY	
Ground-water flow conditions	
Relative ground-water traveltimes in deep sections from potential host rocks to natural discharge areas are very long.	Subsurface data on hydrologic properties of rocks and hydraulic gradients are sparse.
	Much of the area is underlain by carbonate rocks which complicate the flow system.
Intermediate discharge points from potential host rocks to major discharge areas generally are not present.	Intermediate discharge points from potential host rocks to major discharge areas occur in the southern part of ground-water unit DV–03.
Ground-water discharge in the entire area, except ground-water unit DV–01, is to closed basins, offering total containment of waste in one basin.	Underflow occurs from ground-water unit DV–01.
Containment of waste in thick, unsaturated sections in basin fill or rock could add significantly to traveltimes.	
Changes in boundary conditions	Increase in ground-water level during pluvial cycle will tend to decrease the area of potential host rocks in the unsaturated zone and increase ground-water velocity.
Ground-water supply	
Crystalline rocks generally are not explored to depths greater than 100 m for water supply.	Basin fill, basaltic and tuffaceous rocks, sandstone, and carbonate rocks may yield small to moderate quantities of water. Large quantities of water are available locally.
	Ground-water withdrawal near Las Vegas in ground-water unit DV–01 and in Pahrump Valley in ground-water unit DV–03 has caused depressions in the water tables.

TABLE 10.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Death Valley region, Nevada and California*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GEOCHEMISTRY	
Water quality	
Discharge areas of most units have dissolved-solids concentration of more than 3,000 mg/L.	Ground water away from discharge areas generally contains less than 1,000 mg/L dissolved solids in most units.
Ground-water quality is poor in the southwestern part of ground-water units DV–03 and DV–07, with more than 1,000 mg/L dissolved solids.	
Retardation of radionuclides	
Zeolitic tuffs and tuffaceous and clayey alluvium would afford retardation of radionuclides.	Deep flow paths are through carbonate rocks in much of the region where radionuclide retardation may be low.
MINERAL AND ENERGY RESOURCES	
There is no oil or gas production in the region.	Historically, this region has produced substantial amounts of mineral commodities.
Mineral production is sparse.	
	Mineral production is current in ground-water units DV–01, DV–07, and DV–09.
	Known Geothermal Resource Areas are present in ground-water units DV–05 and DV–07.

Radionuclides that are carried in solution from a repository would be diluted in the carbonate-rock aquifer. Ground-water flux is small and movement is relatively slow in the unsaturated zone. Traveltime is largely a function of the recharge rate, distance to the water table, and percent saturation of the unsaturated zone.

Section DV–B (pl. 1) represents hydrogeologic environments similar to those in the western part of ground-water unit DV–03 and other units that are not underlain by a carbonate-rock aquifer.

Environments in tuff, basin fill, and granitic rocks are shown diagrammatically in section DV–B (pl. 1). These rocks are potential hosts for radioactive waste in the unsaturated zone; granitic rocks and tuff are also potential host rocks in the saturated zone. Recharge may be virtually zero in much of the area. The very small flux of water in the unsaturated zone would act to minimize dissolution and transport of waste to the water table. Retardation of radionuclides would be afforded by clays and zeolitic tuffs in the basin fill and by clay minerals in granitic rocks.

Ground-water velocity in crystalline igneous rocks is 6×10^{-4} to 3×10^{-6} m/d based on a K/ϕ (ratio of hydraulic conductivity to effective porosity) of 2×10^{-2} to 1×10^{-4} m/d and a hydraulic gradient of 0.03. Based on these velocities, the traveltime over a distance of 10 km would be 4.6×10^{4} to 9×10^{6} yr. Ground-water velocity in the matrix of unfractured zeolitic or friable tuff, having a moisture content of 0.30 percent, would be 9×10^{-5} m/d for a recharge rate of 10 mm/yr or 9×10^{-5} m/d for a recharge rate of 0.1 mm/yr. The traveltime through 200 m of unsaturated zone, therefore, would be between 6×10^{3} and 6×10^{5} yr for recharge rates between 0.1 and 10 mm/yr.

Ground-water velocity in the flow systems from potential host rocks to the discharge areas will be greatest in the carbonate-rock aquifer. Velocity in the carbonate-rock aquifer would range from 3×10^{-4} to 3×10^{-3} m/d assuming a K/ϕ of 1×10^{-1} to 1×10^{0} md and a hydraulic gradient of 0.003. Traveltime over a distance of 60 km accordingly would be about 5.5×10^{5} to 5.5×10^{4} yr. Large-scale heterogeneities in carbonate rocks locally may decrease traveltime by several orders of magnitude. Accordingly, estimates of traveltime in carbonate rocks should be conservatively small, pending additional data on distribution of hydraulic properties.

Death Valley is the ultimate discharge area for ground-water unit DV–03 and may also receive ground-water inflow from surrounding ground-water units. The valley itself is included in the area of study because it is the terminal discharge point for a large part of the region. The valley is not considered a potential repository environment, but the mountain ranges bordering the valley contain potential host media, chiefly granitic rocks.

All ground-water units, except DV–02, contain large areas of potential host rock. Host media are primarily granitic rocks in ground-water units DV–04, DV–05, DV–06, and DV–08 but also include unsaturated basalt and tuff in ground-water units DV–01, DV–03, DV–07, and DV–09. In addition, ground-water units DV–01 and DV–03 contain large areas of unsaturated basin fill. Ground-water unit DV–02 and adjacent areas in unit DV–03 have insufficient host rock to be considered favorable for further study.

Crystalline rocks afford potential for radionuclide retardation by sorption on clay minerals in weathered zones, fault zones, and argillic altered minerals. The basin fill containing clays and zeolitic tuffs is also a retardant to radionuclide migration.

Earthquakes and Quaternary faults are locally significant and would need to be assessed for individual sites in the region. Long-term vertical crustal movement in most of the units in the region is as great as 4 m per 10,000 yr.

Processes of erosion and aggradation will be more active in this region than in others because of the greater long-term vertical crustal movement. Target repository depths in upthrown blocks should allow for potential erosion rates as great as 4 m per 10,000 yr; on downthrown blocks they should take into account aggradation of the site and possible decrease in depth to water. Quaternary volcanism is present but sparse.

Geothermal springs, primarily in ground-water unit DV–03, represent convective heat flow by ground water. Heat flow has been measured to be greater than 2.5 HFU in ground-water units DV–03 and DV–05.

The potential for ground-water use is present in basin fill where ground-water quality is good. Ground-water potential in host-rock areas is small because water commonly is at great depth. Mining activity occurs locally in the region.

A recurrence of pluvial conditions could increase recharge two- to ten-fold and refill lakes that existed during one or more of the last pluvial periods. Water-level response in the carbonate-rock aquifer, assumed to be under artesian conditions, and in the basin fill would be relatively rapid. Head response in the crystalline rock to boundary changes would vary depending on the hydraulic diffusivity and the geometry of the flow systems. Because of the differences in hydraulic diffusivity, the response in crystalline rock may vary from rapid to very slow. In lieu of firm estimates of the change in recharge during a pluvial climate, a conservative estimate would be a tenfold increase in recharge.

CONCLUSIONS

Potential host media in the Death Valley region include tuffs and crystalline intrusive rocks in the saturated and unsaturated zones, and basalts and basin fill in the unsaturated zone. Ground-water traveltimes in the arid environment with retardation of radionuclides by sorption probably will afford long-term isolation from the near-surface environment. Tectonic activity is of concern in siting, especially in the western tier of ground-water units (DV–04, DV–05, DV–06, DV–08, and DV–09). Additional studies in these areas would be needed to thoroughly assess hazards posed by volcanic activity, seismicity, and faulting.

Ground-water quality in the region, except for high-dissolved solids in a few of the terminal discharge areas, is suitable for most uses. Crystalline intrusive rocks have low water-yielding capacity, and the great depth to water beneath the potentially unsaturated host rocks would discourage development of water supplies. A recurrence of pluvial conditions would not significantly shorten flow paths from most potential host rocks, but an increase in recharge and ground-water levels would reduce

both traveltime and depth to water. The reduction in traveltime would not be significant in the areas underlain by crystalline rocks but might be significant in areas underlain by carbonate rock.

Because of the large areas of unsaturated rock, the abundance of tuff and granite, and the very long traveltimes to discharge areas, ground-water units DV–03, DV–07, and DV–09 appear most prospective for further study.

BONNEVILLE REGION, UTAH AND NEVADA

SUMMARY OF GEOLOGIC AND HYDROLOGIC FACTORS

The Bonneville region has an area of 23,100 km^2 in western Utah and eastern Nevada (pl. 7). The geologic and hydrologic characteristics of the region are summarized in table 11. The potentially favorable factors for waste isolation and corresponding issues of concern for each factor considered in the regional phase of screening are given in table 12.

HYDROGEOLOGIC ENVIRONMENTS

A hydrogeologic environment, which occurs in the Bonneville region, is shown in plate 1. The environments chosen for discussion are in a geologic terrane of predominantly Paleozoic carbonate rocks underlain by Precambrian sedimentary and metasedimentary rocks. The area has been intruded by Tertiary igneous rocks, and Tertiary volcanic rocks cap some of the mountains. Thrusting during the Sevier orogeny (Jurassic to Tertiary) occurred at approximately right angles to the line of section; this was followed by normal faulting in middle Tertiary time, which is largely responsible for the present basin-and-range topography.

Recharge in the arid climate of the region is mostly derived from the precipitation received in the higher parts of the mountain ranges. The carbonate rocks at depth subdrain a large part of the region as typified by hydrogeologic section BV (pl. 1); consequently: (1) The depth to water is relatively great over much of the area; (2) ground water in some of the closed topographic basins drains vertically downward rather than discharging at the surface; (3) flow paths from the ground-water divide are very long; and (4) the hydraulic gradient is very low.

Potential host media in section BV (pl. 1) include granitic intrusions and tuff. Ground-water traveltimes from the potential host rocks to the discharge areas in the cabonate-rock aquifer may be on the order of 10^4 or 10^5 yr. The velocity of ground-water movement in the granite pluton probably would be within the range of 1.5×10^{-5} to 6×10^{-4} m/d. The traveltime from near the divide in the granitic pluton to the carbonate rock may be from 1.8×10^6 to 4.5×10^4 yr. This estimate is based on a K/ϕ (ratio of hydraulic conductivity to effective porosity) of from 5×10^{-4} to 2×10^{-2} m/d, a hydraulic gradient of 0.03, and a distance of 10 km. Retardation by sorption of radionuclides may increase the traveltime in granite and in shales interbedded with carbonate rocks. Traveltime in the unsaturated part of the granitic body from 200 m above the water table could add 60–6,000 yr to the total traveltime. However, in an arid environment with a very low or no flux rate, contact of the waste with water would be minimal.

Velocity of water movement in tuff varies greatly depending on whether the tuff is welded and fractured with a small porosity and moisture content or whether it is friable pumiceous or zeolitic tuff with a large porosity and moisture content.

Velocity in the unsaturated zone of the tuffaceous rocks depends upon the moisture content and flux rate. Estimates of velocity for a welded tuff could be between 2.7×10^{-4} and 2.7×10^{-2} m/d with a traveltime between 2×10^1 and 2×10^3 yr through an unsaturated thickness of 200 m above the water table; whereas the velocity in a zeolitic tuff could be between 8×10^{-7} and 8×10^{-5} m/d with a traveltime of 7×10^3 to 7×10^5 yr for an unsaturated thickness of 200 m. Velocities of ground water in the saturated tuff also vary greatly depending upon the nature of porosity and permeability. Velocities for a friable, highly porous tuff and for a fractured welded tuff may be on the order of 2×10^{-10} m/d and 8×10^{-3} m/d, respectively.

Ground-water velocities in the carbonate-rock aquifer underlying the region are on the order of 2.5×10^{-2} to 2.5×10^{-1} m/d based on K/ϕ of 5×10^0 to 5×10^1 m/d and a hydraulic gradient of 0.005. Ground-water traveltime through a distance of 40 km would be 4.4×10^4 to 4.4×10^2 yr.

Except for ground-water unit BV–03, the region is largely free from concerns of tectonic instability that would accelerate the transport of radionuclides. The warm springs of the discharge areas shown in section BV (pl. 1) represent heat convection by deep ground-water circulation in the carbonate-rock aquifer. Vertical crustal movement is moderately low and probably would not be accompanied by erosion processes that would imperil a repository at a depth as shallow as 300 m over a period of 100,000 yr.

A recurrence of pluvial conditions potentially would refill Pleistocene Lake Bonneville to the Provo level. This would inundate about one-half of the surface in section BV (pl. 1) and reduce the length of travel paths. Increased recharge also would raise ground-water levels and reduce the thickness of the unsaturated zone.

TABLE 11.—*Summary of geologic and hydrologic characteristics of the Bonneville region, Utah and Nevada*
[km^2, square kilometer; m, meter; mm/yr, millimeter per year; <, less than; mg/L, milligram per liter]

Characteristic	Ground-water unit					Comments
	BV–01	BV–02	BV–03	BV–04	BV–05	
PHYSIOGRAPHY						
Area, in km^2	11,000	3,700	4,000	3,000	1,400	Altitudes in the Bonneville region range from approximately 1,300 m to greater than 3,600 m. Mountain ranges generally are less than 2,500 m. Mountains cover about 25 percent of the area, basins cover about 40 percent, and gravel fans cover about 35 percent.
Area of basin fill, in km^2	5,250	1,850	2,250	1,150	500	Precipitation generally is less than 200 mm/yr in the northern part of the region and 200–300 mm/yr in the southern part. Precipitation in some of the mountains is greater than 600 mm/yr.
Evaporation						Mean-annual free-water-surface evaporation for the area is primarily 1,500–2,000 mm/yr; it is 1,000–1,250 mm/yr in some parts of the area.
POTENTIAL HOST ROCK						
Granitic rocks						
Total outcrop area, in km^2	130	150	50	110	<10	Unsaturated granitic rocks occur in all ground-water units.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	120	140	30	80	0	
Unsaturated zone greater than or equal to 150 m thick:						
Basaltic rocks						
Total outcrop area, in km^2	60	0	0	0	0	Basalt flows as thick as 150 m crop out in BV–01.
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	60	0	0	0	0	
Tuffaceous rocks						
Total outcrop area, in km^2	560	0	10	0	0	Ash-flow tuff units as thick as 900 m occur in BV–01. Aggregate thickness may be as great as 5,000 m.

TABLE 11.—*Summary of geologic and hydrologic characteristics of the Bonneville region, Utah and Nevada*—Continued

Characteristic	Ground-water unit BV–01	BV–02	BV–03	BV–04	BV–05	Comments
POTENTIAL HOST ROCK—Continued						
Tuffaceous rocks—Continued						
Total area, in km^2, of contiguous outcrops that are greater than 6.5 km^2.	530	0	0	0	0	Ash-flow tuff as thick as 1,000 m may occur in BV–03.
Argillaceous rocks						
Total outcrop area, in km^2	110	110	0	80	40	
Total area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	60	110	0	40	30	
Areas underlain by unsaturated basin fill greater than or equal to 150 m thick.						
Total outcrop area, in km^2	630	90	140	190	160	
Total outcrop area of potential host rock (does not include shales or unsaturated basin fill).						
Total surface area, in km^2	750	150	60	110	<10	
Total surface area, in km^2, of contiguous outcrops that are more than 6.5 km^2.	710	140	30	80	0	
QUATERNARY TECTONIC ACTIVITY						
Strain release						
Strain release greater than 10 occurs in unit.	NO	NO	NO	NO	NO	BV–03 and BV–04 each had one earthquake of magnitude 4.3. Two swarms of generally less than magnitude 4 earthquakes have been recorded in the region: one in BV–03 and one in the Snake Range in BV–01 and BV–02.
Percent of outcrop area of potential host rock within 10 km of strain release more than 10.	0	0	0	0	0	
Vertical crustal movement						
Long term						
Uplift of greater than 4 m per 10^4 yr occurs within unit.	YES	YES	NO	YES	YES	
Percent of outcrop area of potential host rock with uplift of greater than 4 m per 10^4 yr.	10	50	0	40	0	

TABLE 11.—*Summary of geologic and hydrologic characteristics of the Bonneville region, Utah and Nevada*—Continued

Characteristic	Ground-water unit BV–01	BV–02	BV–03	BV–04	BV–05	Comments
QUATERNARY TECTONIC ACTIVITY—Continued						
Vertical crustal movement—Continued						
Short term						
Movement of greater than 4 mm/yr based on geodetic leveling.	NO	NO	NO	NO	NO	
Percent of outcrop area of potential host rock with movement of greater than 4 mm/yr based on geodetic leveling.	0	0	0	0	0	
Quaternary faults						
Quaternary fault(s) occurs in unit.	YES	YES	YES	YES	NO	
Percent of outcrop area of potential host rock within 10 km of Quaternary fault.	10	50	0	0	0	
Heat flow						
Heat flow greater than 2.5 heat flow units occurs within unit.	YES	NO	YES	NO	NO	
Percent of outcrop area of potential host rock within 10 km of heat flow greater than 2.5 heat flow units.	20	0	20	0	0	
Quaternary volcanism						
Quaternary volcanism occurs within unit.	NO	YES	YES	YES	YES	
Percent of outcrop area of potential host rock within 10 km of Quaternary volcanism.	0	0	0	10	0	
GEOMORPHIC PROCESSES						Climatic change may cause stage rise of closed-basin lakes.
GROUND-WATER HYDROLOGY						
Ground-water flow conditions						
Common values of relative ground-water traveltime near the water table from areas of potential host rock to natural discharge areas.	1–5, 5–10	1–5	1–5	1–5	0–1	The region contains numerous warm springs or large springs, most of which are located in major ground-water discharge areas.
Longest relative travel-time near the water table from areas of potential host rock to natural discharge areas.	10–20	1–5	1–5	1–5	0–1	Most traveltimes in BV–01 are calculated to ground-water sinks. Actual times could be significantly longer.

TABLE 11.—*Summary of geologic and hydrologic characteristics of the Bonneville region, Utah and Nevada*—Continued

Characteristic	Ground-water unit BV–01	BV–02	BV–03	BV–04	BV–05	Comments
GROUND-WATER HYDROLOGY—Continued						
Changes in boundary conditions.						
Part of area inundated by Pleistocene lake.	YES	YES	YES	YES	YES	
Percent of outcrop area of potential host rock inundated by Pleistocene lake.	<1	20	65	3	0	
Ground-water supply						Basin-fill deposits, basaltic and tuffaceous rocks, and sandstone may yield small to moderate quantities of water. Carbonate rocks underlying much of the area locally may provide moderate to large quantities of water. Basin fill locally may yield large quantities of water. No major ground-water withdrawal occurs in the region.
GEOCHEMISTRY						
Water quality						
Area of basin fill containing dissolved-solids content of:						
Less than 500 mg/L	4,250	1,850	300	1,150	150	
500–1,000 mg/L	700	0	750	0	100	
1,000–3,000 mg/L	300	0	1,000	0	200	
3,000–10,000 mg/L	0	0	200	0	50	
More than 10,000 mg/L	0	0	0	0	0	
Retardation of radionuclides						Deep flow paths are through carbonate rocks in much of the region. Radionuclide retardation may be slight.
MINERAL AND ENERGY RESOURCES						
Percent of potential host rock outcrop area coincident with mineral resource area.	16	20	67	36	0	Most mineral resource areas contain base and precious metals in deposits of limited extent. Large deposits of low-grade beryllium are presently mined in the south-central part of BV–03. Gold is being mined in the eastern part of BV–01. There are no producing oil or gas wells, coal deposits, or developed geothermal resources in the region.

TABLE 12.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Bonneville region, Utah and Nevada*

[km^2, square kilometer; m, meter; yr, year; mm/yr, millimeter per year; mg/L, milligram per liter]

Potentially favorable hydrogeologic factors	Issues of concern and study needs
POTENTIAL HOST ROCKS	
Granitic rocks have outcrop areas of more than 100 km^2 in ground-water units BV–01, BV–02, and BV–04.	Potential host rocks are limited in ground-water units BV–03 and BV–05.
Unsaturated basaltic rocks occur in in ground-water unit BV–01.	
Unsaturated tuffaceous rocks are abundant in ground-water unit BV–01.	
QUATERNARY TECTONIC ACTIVITY	
The area has no strain release greater than 10.	Three magnitude 4–5 earthquakes were recorded in the region.
	Two swarms of generally less than magnitude 4 earthquakes have been recorded in the region, one in ground-water unit BV–03 and one in the western parts of ground-water units BV–01 and BV–02.
Vertical crustal movement is small throughout ground-water units BV–01, BV–03, and BV–05.	Long-term vertical crustal movement is more than 4 m per 10^4 yr in the western parts of ground-water units BV–02 and BV–04.
The 2 mm/yr line of vertical movement in eastern Bonneville region is related to rebound following drainage of Lake Bonneville and probably does not indicate any adverse activity.	
Quaternary faults are sparse in ground-water units BV–01, BV–03, BV–04, and BV–05.	
Geothermal heat flow is generally less than 2.5 heat flow units in the region.	Geothermal heat flow is greater than 2.5 heat flow units in the southernmost part of ground-water unit BV–01 and in a large part of ground-water unit BV–03.
GEOMORPHIC PROCESSES	
Denudation of the surface at a maximum rate equal to the long-term rate of 2–4 m per 10^4 yr, which is the higher rate for most of the region, would not reduce effectiveness of a waste-isolation environment at a depth as shallow as 300 m over a period of 100,000 yr.	
Larger, short-term, local rates of uplift are not expected to persist for periods long enough to affect integrity of a repository.	

TABLE 12.—*Potentially favorable hydrogeologic factors and issues of concern and study needs relative to isolation of high-level radioactive waste in the Bonneville region, Utah and Nevada*—Continued

Potentially favorable hydrogeologic factors	Issues of concern and study needs
GROUND-WATER HYDROLOGY	
Ground-water flow conditions	
Relative ground-water traveltimes from potential host rocks to natural discharge areas are very long.	Subsurface data on hydrologic framework and data on hydraulic properties of rocks and hydraulic gradients are sparse.
Hydraulic gradients in the carbonate rocks are very low, creating long traveltimes.	Much of the area is underlain by carbonate rocks which complicate the flow system.
Ground-water discharge in the entire area is to closed basins, offering total ultimate containment of waste in the region.	Containment within one basin precludes dilution at discharge areas.
	Underflow occurs between some topographically closed basins.
Changes in boundary conditions	
	Ground-water velocities during pluvial periods will increase in response to increases in recharge and hydraulic gradients.
	Pluvial lakes have inundated parts of all units. Large areas of potential host rocks could be inundated in ground-water units BV–02 and BV–03.
Ground-water supply	
Granitic rocks are negligible or minor sources of water supply.	Basin-fill deposits, basaltic and tuffaceous rocks, and sandstones locally may yield small to moderate quantities of water. Basin fill locally yields large quantities of water.
Expense and problems associated with drilling deep wells tend to prevent inadvertent intrusion of deep carbonate-rock aquifers.	Carbonate rocks may provide moderate to large quantities of water.
GEOCHEMISTRY	
Water quality	
Approximately one-half of the basin fill in ground-water unit BV–03 contains ground water with dissolved-solids concentration of more than 1,000 mg/L.	Ground water in basin-fill deposits generally contains less than 3,000 mg/L dissolved solids.
Retardation of radionuclide migration	
Zeolitic tuffs and tuffaceous and clayey alluvium would afford radionuclide retardation.	Deep flow paths are through carbonate rocks in much of the region where radionuclide retardation may be low.
MINERAL AND ENERGY RESOURCES	
Most mineral resource areas contain base and precious metals in deposits of limited extent.	Large deposits of low-grade beryllium are being mined in the south-central part of ground-water unit BV–03.
There are no producing oil or gas wells, coal deposits, or developed geothermal resources in the region.	Gold is being mined in the eastern part of ground-water unit BV–01.

The ground-water potential for water supply is poor in the granitic rocks because of the low permeability. Water supplies of good quality are available from the carbonate rocks and basin fill. Supplies may be low in the basin fill, however, because of the lower permeability in the saturated lower part of the deposits. The permeability distribution in the carbonate rocks is not known, and exploitation may be discouraged by large exploration costs.

CONCLUSIONS

Environments containing intrusive and tuffaceous igneous rocks in ground-water units BV–01, BV–02, and BV–04 are prospective for further study in the Bonneville region, Utah and Nevada. Most of the region is subdrained by a carbonate-rock aquifer through which traveltime is probably longer than in the crystalline rock of the region. The host rock may provide the greatest portion of the long traveltime desired (more than 100,000 yr) to the accessible environment. Low permeability and radionuclide sorptive barriers are not identified beyond the potential host rocks, although the carbonate rocks contain some clay interbeds. Discharge from the carbonate-rock aquifer is believed to occur predominantly at a few large springs. Although the recurrence of Pleistocene pluvial conditions would greatly reduce the length of travel path from host rock to discharge area, the travel path reduction would be in the carbonate-rock aquifer. The region is relatively quiet tectonically, except for ground-water unit BV–03. Water-supply potential is known in the upper part of the basin fill, and the water quality is good over most of the region. The carbonate rock has water-supply potential but is not tapped at the present time. Water-supply potential is poor in the candidate granitic host rocks.

Because most flow from the system is concentrated at large springs, an alternative environment for waste isolation may exist. This environment is beneath the very large area of the Great Salt Lake Desert, where the ground-water flux is very low, away from the areas of concentrated discharge. Because of the large area and very low flux, the very low to nil upward velocity of ground water would afford very long traveltimes. The presence of potential host rock beneath the Great Salt Lake Desert has not been explored.

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U.S. GEOLOGICAL SURVEY

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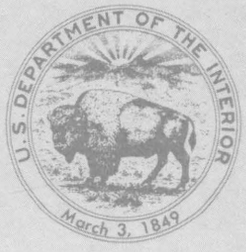
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