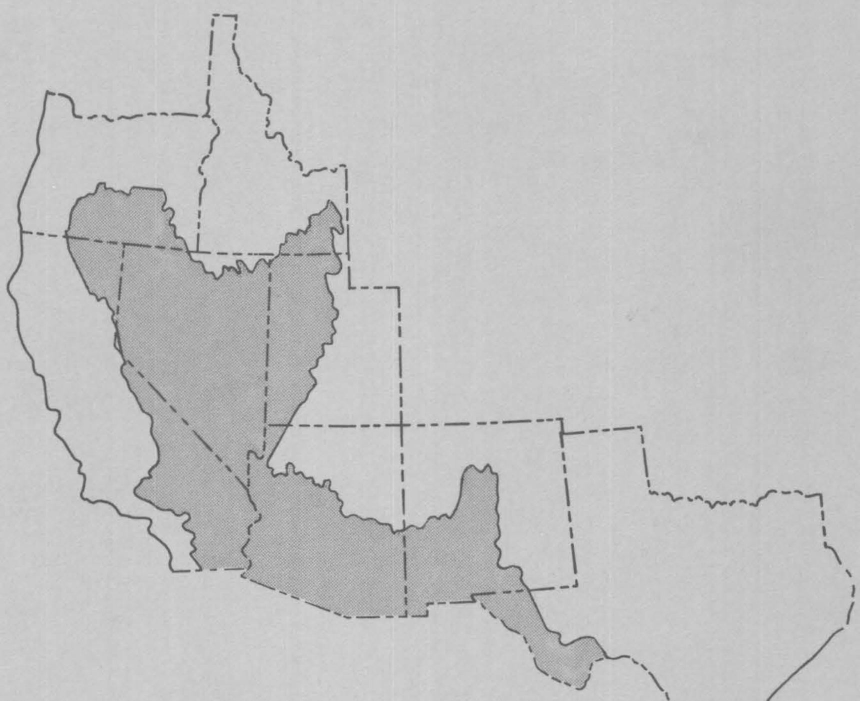
Geologic and Hydrologic Characterization and Evaluation of the Basin and Range Province Relative to the Disposal of High-level Radioactive Waste

Part II Geologic and Hydrologic Characterization



GEOLOGICAL SURVEY CIRCULAR 904-B

This is Part II of a series of reports being prepared by the U.S. Geological Survey in consultation with States in the Basin and Range Province.

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

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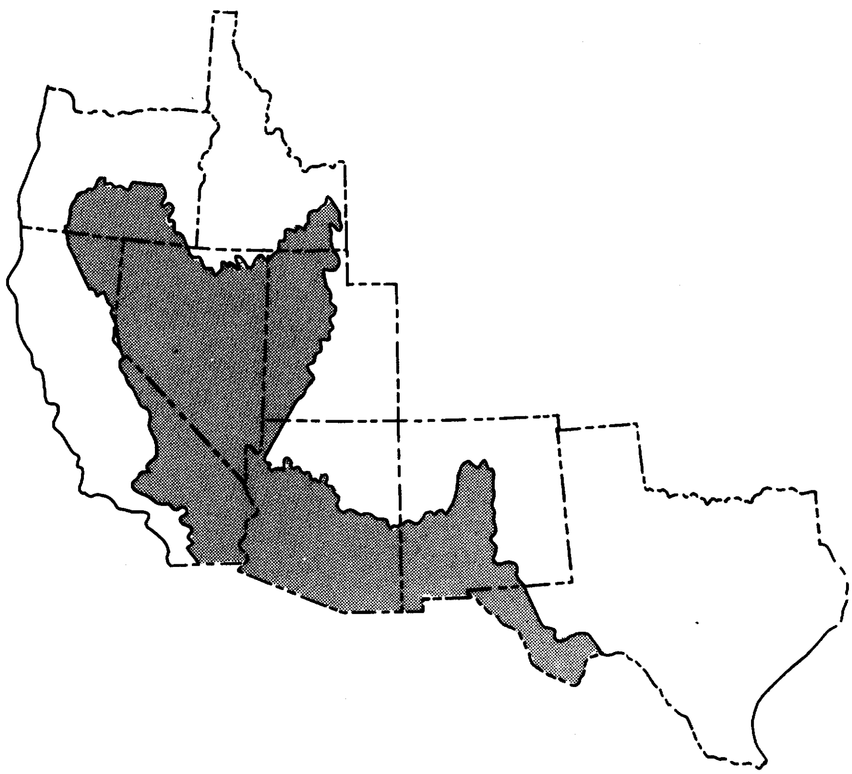
By K. A. Sargent and M. S. Bedinger



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United States Department of the Interior
WILLIAM P. CLARK, *Secretary*

Geological Survey
Dallas L. Peck, *Director*

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CONTENTS

ILLUSTRATIONS

CONVERSION FACTORS

Metric unit		Conversion factor		English unit
square kilometer (km^2)	X	0.386	=	square mile (mi^2)
meter (m)	X	3.281	=	foot (ft)
kilometer (km)	X	0.621	=	mile (mi)
millimeter (mm)	X	0.039	=	inch (in.)

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

PART II
GEOLOGIC AND HYDROLOGIC CHARACTERIZATION

by
K. A. Sargent and M. S. Bedinger

SUMMARY

The geology and hydrology of the Basin and Range Province of the western conterminous United States are characterized in a series of data sets depicted in maps compiled for evaluation of prospective areas for further study of geohydrologic environments for isolation of high-level radioactive waste. The data sets include: (1) Average precipitation and evaporation; (2) surface distribution of selected rock types; (3) tectonic conditions; and (4) surface- and ground-water hydrology and Pleistocene lakes and marshes.

Rocks mapped for consideration as potential host media for the isolation of high-level radioactive waste are widespread and include argillaceous rocks, granitic rocks, tuffaceous rocks, mafic extrusive rocks, evaporites, and laharic breccias. The unsaturated zone, where probably as thick as 150 meters (500 feet), was mapped for consideration as an environment for isolation of high-level waste. Unsaturated rocks of various lithologic types are widespread in the Province.

Tectonic stability in the Quaternary Period is considered the key to assessing the probability of future tectonism with regard to high-level radioactive waste disposal. Tectonic conditions are characterized on the basis of the seismic record, heat-flow measurements, the occurrence of Quaternary faults, vertical crustal movement, and volcanic features. Tectonic activity, as indicated by seismicity, is greatest in areas bordering the western margin of the Province in Nevada and southern California, the eastern margin of the Province bordering the Wasatch Mountains in Utah and in parts of the Rio Grande valley. Late Cenozoic volcanic activity is widespread, being greatest bordering the Sierra Nevada in California and Oregon, and bordering the Wasatch Mountains in southern Utah and Idaho.

The arid to semiarid climate of the Province results in few perennial streams and lakes. A large part of the surface drainage is interior and the many closed basins commonly are occupied by playas or dry lake beds. The Province is divided into ground-water flow units defined on the basis of ground-water divides, ground-water flow lines, and surface streams that receive ground-water discharge.

Ground water contains less than 500 milligrams per liter of dissolved solids throughout most of the Province. Ground water is more mineralized in areas underlain by evaporitic rocks, overlain by playas, and near saline lakes. Ground water is of the calcium, magnesium, or sodium bicarbonate type in the areas where dissolved-solids concentrations are less than 500 milligrams per liter, and of the calcium, magnesium, or sodium sulfate or chloride type where dissolved-solids concentrations are greater than 500 milligrams per liter.

Geologic and hydrologic evidence is found for about 100 lakes and marshes that existed during the Pleistocene Epoch. The possibility of a recurrence of pluvial conditions, such as existed in the Pleistocene, is of concern in repository siting because of possible changes in hydrologic conditions. The Pleistocene lakes and marshes provide clues to the hydrology during pluvial climates.

INTRODUCTION

This second part of a three-part report describes the information compiled to characterize the geology and hydrology of the Basin and Range Province (fig. 1). The boundary of the Basin and Range Province, as used for this study, closely follows the physiographic province defined by Fenneman (1928). The boundary, as used here, follows the natural ground-water flow-unit boundaries that define most of the study area. Part I is the introduction to the study and a discussion of the guidelines that will be used in evaluation (Bedinger, Sargent, and Reed, 1983). Part III is the evaluation of the Province (Bedinger, Sargent, and Brady, 1983). Factors selected for characterization in Part II are those that are considered to be significant in identification of suitable environments for waste isolation for which

Base map from
U.S. Geological Survey

FIGURE 1.—Location of the Basin and Range Province as defined for this study (shaded) and geographic features.

approximately comparable data are available for the entire Province. The scope of data sets compiled for Province characterization is thus limited by the extent of information available. Factors selected for characterization included: (1) Surface distribution of selected rock types including fine-grained detrital rocks and their metamorphic equivalents, granitic rocks, tuffaceous rocks, mafic extrusive rocks, and evaporites; (2) unsaturated media; (3) tectonic conditions including seismicity, Quaternary faults, late Cenozoic volcanic activity, Quarternary vertical crustal movement, and heat flow; (4) ground-water hydrology; (5) ground-water quality; and (6) Pleistocene hydrologic features. Areal gravity and magnetic data were used to provide supplementary information.

SOURCES AND COMPILATION OF INFORMATION

Sources of geologic and hydrologic information compiled for characterization include published reports, information in files of the U.S. Geological Survey, the U.S. Geological Survey WATSTORE computer file of ground-water information and ground-water chemical analyses, and data in files of other Federal and State agencies.

The following table shows information covered in previously published reports of the U.S. Geological Survey. These reports have been used in the characterization of the Basin and Range Province.

Information	Geographic Area	Author(s)
Outcrop of argillaceous rocks.	Eastern Nevada	Simpson, Weir, and Woodward, 1979.
Seismic maps	Basin and Range Province.	Algermissen and others, 1983; Askew and Algermissen, 1983.
Quaternary faults.	Basin and Range Province.	Nakata, Wentworth, and Machette, 1982.
Quaternary volcanic rocks.	Arizona and New Mexico	Luedke and Smith, 1978a.
	Colorado, Utah, and southwestern Wyoming	Luedke and Smith, 1978b.
	California and Nevada	Luedke and Smith, 1981.
	Oregon and Washington	Luedke and Smith, 1982.
Quaternary vertical crustal movement.	Basin and Range Province, conterminous United States.	Gable and Hatton, 1980.
Heat flow	Basin and Range Province.	Sass and others, 1976.
Geothermal resources	United States	Muffler, L.J.P., editor, 1979.

Published reports of State and other Federal agencies were used also. These include the list of thermal springs of the United States compiled by Berry, Grim and Ikelman (1980).

The rock outcrop maps and information on lithology, thickness and age were compiled by the following members of the U.S. Geological Survey, Lakewood, Colorado: Kenneth A. Sargent, Jane J. Dickson, William D. Johnson, Judith S. Gassaway, David A. Lopez, and F. Allan Hills. Rock outcrop maps for Texas were compiled by Christopher D. Henry and Gail L. Fisher of the Texas Bureau of Economic Geology. Laharic breccias and volcanic rocks of New Mexico were compiled under the direction of John Hawley of the New Mexico Bureau of Mines and Mineral Resources.

Thomas G. Hildenbrand, U.S. Geological Survey, Lakewood, Colorado, compiled areal geophysical information on gravity and magnetics data.

Most of the information on hydrology and quality of ground water was compiled by hydrologists in the following offices of the U.S. Geological Survey: Thomas Anderson of the Tucson, Arizona, District Office directed compilation of data for Arizona; Richard Ireland in the Sacramento, California, District Office compiled information for northern California; Richard Moyle and Lynda Woolfenden of the Laguna Nigel, California, office compiled information for southern California; Joseph Gates, James Stark, and James Mason of the Salt Lake City, Utah, District Office compiled information for Utah and Idaho; James Harrill, James Thomas, and Allan Welch of the Carson City, Nevada, office compiled information for Nevada; Donald Hart of the Albuquerque, New Mexico, District Office compiled information for New Mexico; Joseph Gonthier and William McFarland of the Portland, Oregon, District Office compiled information for Oregon; Bruce Timothy Brady of the Lakewood, Colorado, office and John Mikels and Donald White of the El Paso, Texas, office compiled information for Texas.

Information on depths to ground water in the Province were examined by William Langer, U.S. Geological Survey, Lakewood, Colorado, who, with the assistance of Deborah Mulvihill, U.S. Geological Survey, Lakewood, Colorado, outlined areas within which the depth to water is probably 150 meters (500 feet) or greater.

Information on the chemical quality of ground water was synthesized and mapped by Thomas Thompson of the U.S. Geological Survey, Lakewood, Colorado, with the assistance of Richard Chappel and Janet Nuter, graduate students of the Colorado School of Mines. Thomas Thompson provided the classification of water-quality types used in this report and the description of areal distribution of water-quality type and dissolved-solids concentrations of ground water.

Thomas Williams, graduate student, Colorado State University, and U.S. Geological Survey, Lakewood, Colorado, compiled information on Pleistocene lakes and marshes.

ACKNOWLEDGMENTS

The State members and alternates of the Province Working Group were the principal consultants and reviewers during the planning, compilation, and preparation for release of the geologic and hydrologic information used to characterize the Province.

The following individuals also are acknowledged for their assistance during various phases of the preparation, compilation, and review of this report: Harry D. Goode, who serves as ground-water consultant to the Utah Geological and Mineral Survey, Salt Lake City, Utah; John Hawley and William Stone of the New Mexico Bureau of Mines and Mineral Resources; Robert B. Scarborough and Stephen J. Reynolds of the Arizona Bureau of Geology and Mineral Technology; Joe Tingley of the Nevada Bureau of Mines and Geology; Charles Jennings of the California Division of Mines and Geology; and Donald Hull, John Beaulieu, and John Bela of the Oregon Department of Geology and Mineral Industries.

CLIMATE AND SURFACE HYDROLOGIC FEATURES

The climate in the Basin and Range Province is arid to semiarid. Seasonal weather patterns are caused by annual variations in the magnitude and movements of air masses from the Pacific Ocean, Gulf of Mexico, and the polar continental region. Prolonged periods of extremely cold weather are rare, primarily because of the mountains north of the Province and the moderating effect of maritime air masses from the Pacific.

The mean annual precipitation is about 28 centimeters (11 inches) (fig. 2). The great variability in the areal distribution of precipitation is directly related to the pattern of topographic relief between the ranges and the intervening basins. Precipitation ranges from less than 10 centimeters (4 inches) in the basins to as much as 30 to 40 centimeters (12 to 16 inches) at higher elevations. The predominant source of moisture during the winter is storms that originate in the north Pacific and move from west to east across the Basin and Range. The Coast Ranges and the Sierra Nevada, to the west of the Basin and Range Province, cause precipitation in the mountains as the moist air masses rise. Descending from the Sierras into the lower elevations of the Basin and Range, the winds are warmed and compressed and as the storms move eastward across the Province, precipitation occurs mostly at higher elevations. Continental polar air masses periodically move southward into the Province from the north, bringing cold, dry air. Precipitation occurs when cold air from the north encounters warm, moist air from the Gulf of Mexico, south Pacific Ocean region, and Gulf of California.

In the summer, the prevalent Pacific high-pressure area drifts northward and Pacific air masses generally are deflected over the continent north of the Province. Consequently, the Province receives relatively little summer precipitation from northern Pacific air masses. In the middle and late summer, storms originating in the Gulf of Mexico, and occasional storms laden with warm, moist air from the southern Pacific region and Gulf of California, move into the southern and southwestern part of the Province.

The potential evaporation greatly exceeds the annual precipitation. The mean annual free-water surface evaporation ranges from 89 to 254 centimeters (35 inches to 100 inches) (fig. 3).

Low precipitation and high water loss by evaporation and transpiration results in little annual runoff (fig. 4) and few perennial streams and lakes. Mean annual runoff from the Basin and Range Province generally is less than 0.5 centimeter (0.2 inch). A few perennial streams within the arid and semiarid parts of the Basin and Range Province originate at the higher elevations in the highlands and ranges within the Province or the bounding ranges, such as the highlands bordering the Colorado Plateau in Arizona and New Mexico, the Sierra Nevada of California, and the Wasatch Range of Utah. Two perennial streams, the Colorado River and the Rio Grande, originate outside the Province and flow through the Province. Surface drainage basins include closed basins with interior drainage and basins with surface drainage to the sea. Closed basins comprise about 80 percent of the surface area of the Province, most ranging in size from a few tens to several hundred square kilometers. A few large closed basins in the Great Basin region of Utah, Nevada, and California, the Great Salt Lake basin, the Death Valley basin, and the Humboldt River basin, have areas of thousands of square kilometers. Perennial streams in these and a few other basins terminate in perennial lakes. Streams in most of the closed basins only convey water from occasional storms to usually dry lakes or playas where water evaporates or infiltrates to the subsurface. Beneath many of the dry lakes, the ground-water level remains below the land surface because of evaporation through the soil and transpiration by plants.

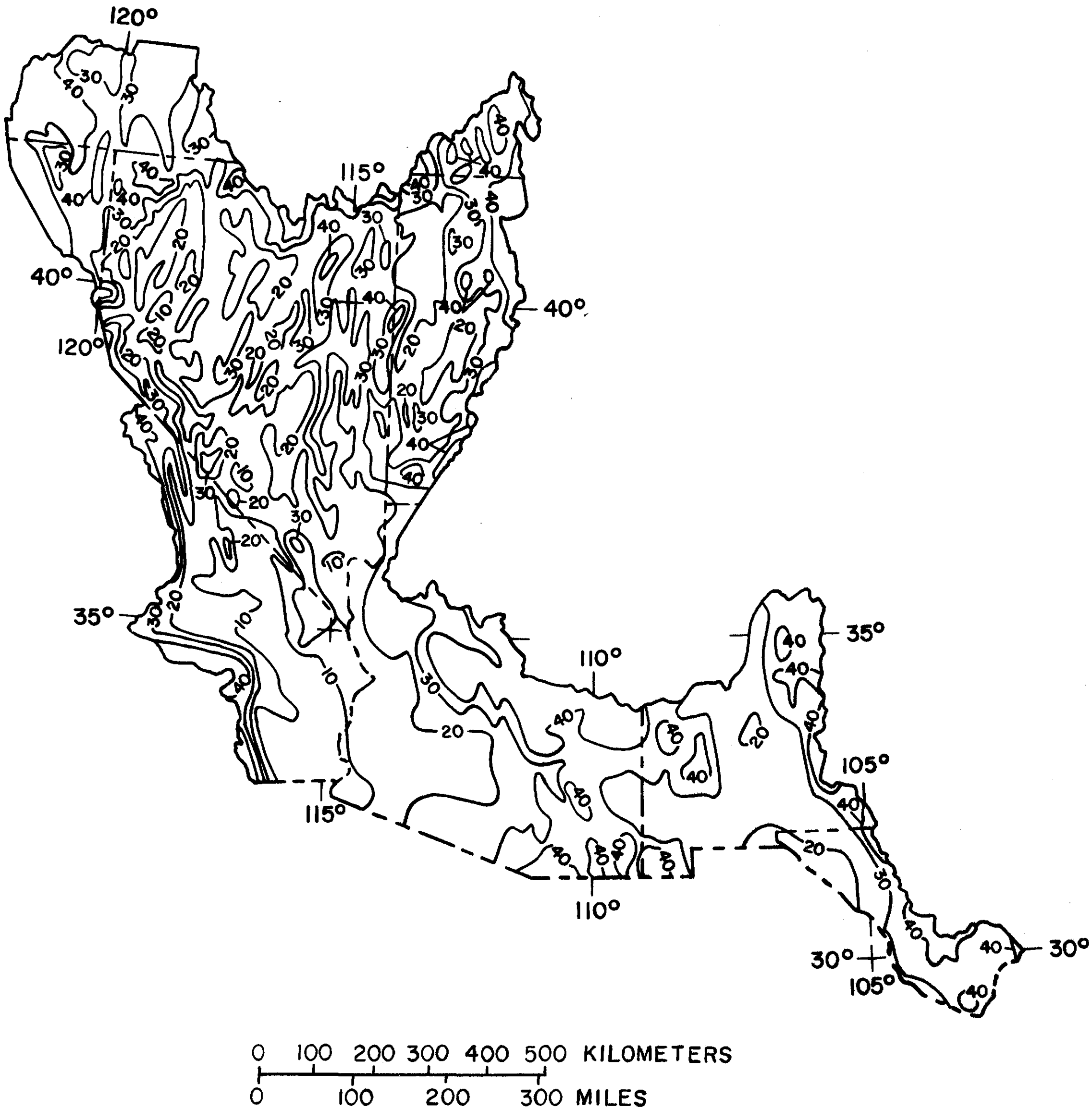


FIGURE 2.—Mean annual precipitation. Interval 10 centimeters. Modified from U.S. Department of Commerce, 1968.

In contrast, beneath some of the dry lakes of closed basins, the depth to ground-water is greater than the effects of surface and plant evapotranspiration, indicating that storm water that infiltrates the soil to the water table becomes part of the ground-water flow system and is discharged in other basins.

The water deficiency of the Province, measured by the excess of potential evapotranspiration compared to precipitation, is a significant characteristic with respect to isolation of radioactive wastes. As a consequence of the climate, ground-water recharge is low. Recharge probably is variable in time occurring during infrequent times of water excess. The areal distribution of recharge is affected by the permeability of outcropping rocks, areas where excess water may be concentrated during brief periods of runoff, and the areas of greater precipitation at higher elevations. As a direct result of slow recharge rates, the unsaturated zone is very thick in some areas and the moisture content and rate of movement in the unsaturated zone are very small. These characteristics enhance the unsaturated zone's capability to isolate radioactive wastes from the accessible environment.

Because of the long duration of toxicity of high-level radioactive wastes, the future climate also is of

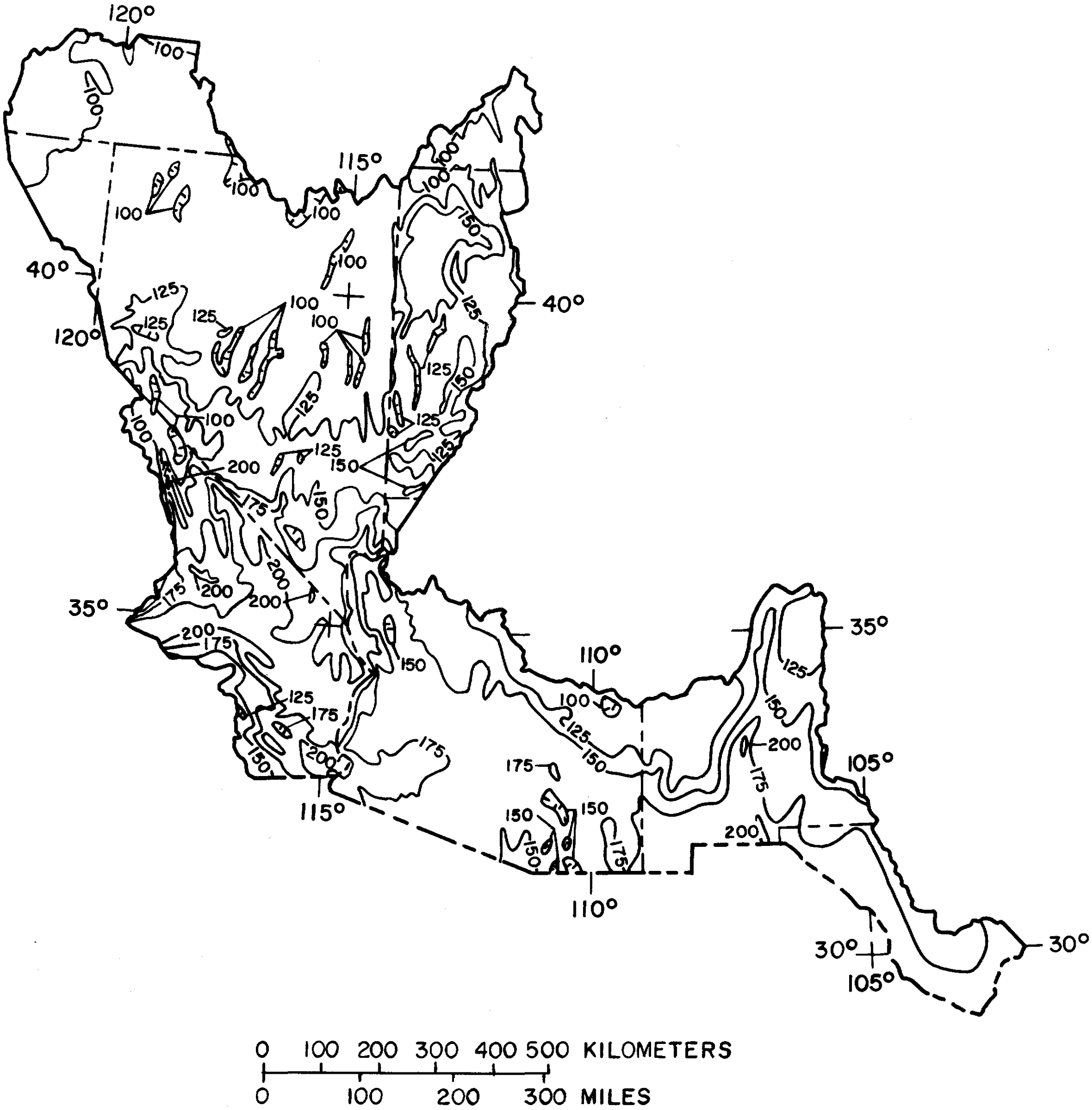


FIGURE 3.—Mean annual free-water surface evaporation. Interval is 25 centimeters. Modified from U.S. Department of Commerce, 1982.

concern in evaluating the Province relative to the isolation of the wastes. Among the evidence that wetter climates existed at times in the past few tens of millenia are the vestiges of nearly 100 abandoned lake shorelines in the Province. These shorelines are as much as several hundred feet higher than present lake levels or the dry lake beds that now occupy the basins. Evidence from Pleistocene lakes (see the section on "Pleistocene hydrologic features") can assist in estimating the magnitude of hydrologic changes that could result from possible future climatic change.

DISTRIBUTION OF SELECTED ROCK TYPES

Several rock types have been considered as potential host media for high level radioactive-waste repositories. Among those that have been studied are the following generic types: shale, granite, tuff, basalt, and salt. Other rock types, generally of less widespread occurrence,

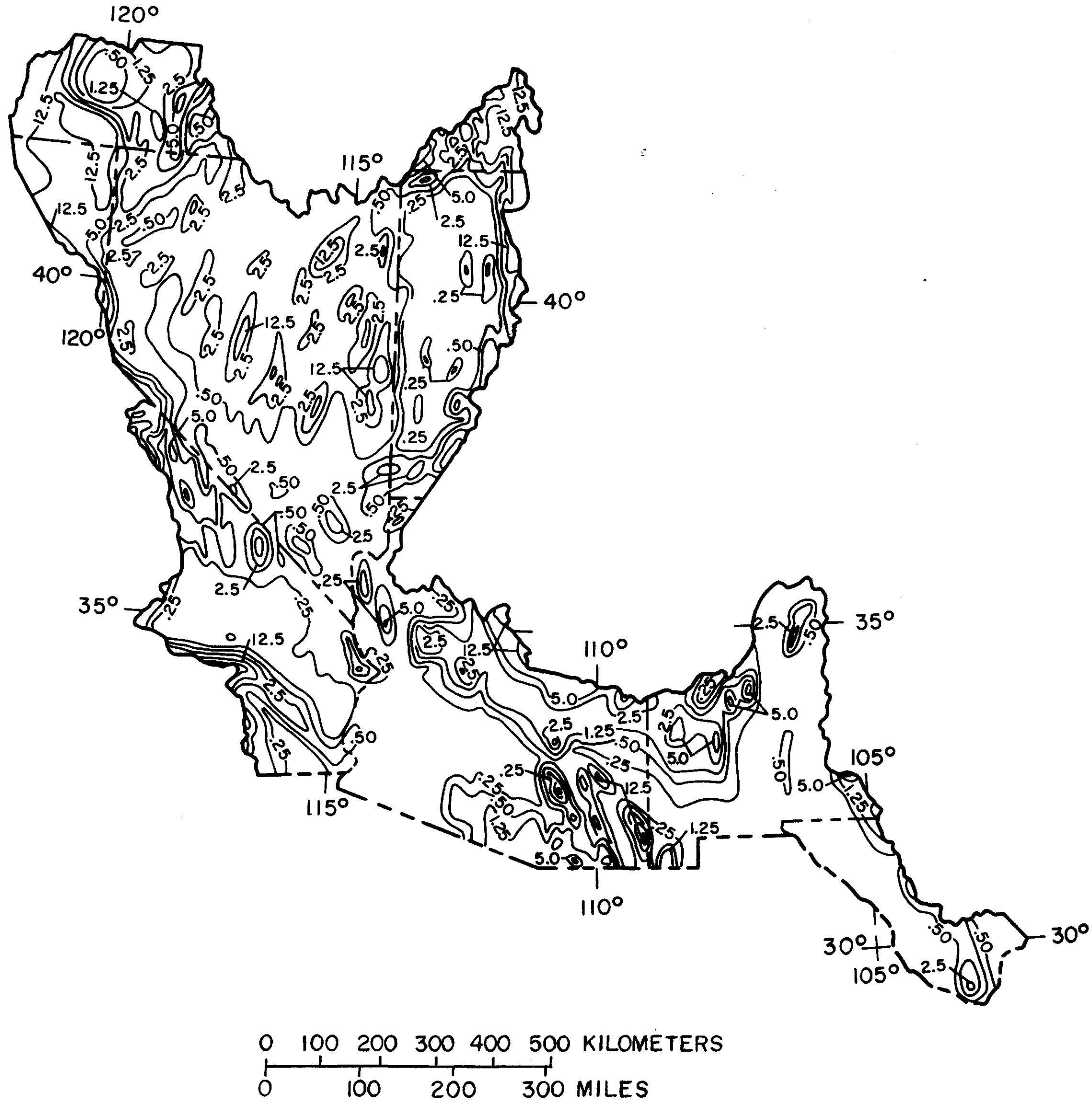


FIGURE 4.—Mean annual runoff. Interval in centimeters is variable. Modified from Busby, 1965.

in the Province have been mapped where, by their physical properties and occurrence, they have potential as host media. In addition, the unsaturated zone, in which several rock types may be suitable, has been the subject of investigation as a distinct repository host medium.

In compiling information about the occurrence of the selected rock types, the surface distribution, thickness (where appropriate), lithology, age, and major published references were compiled. Additional data on the subsurface occurrence, depth, and thickness were compiled for evaporites. The surface outcrop provides an initial perspective of the Province-wide distribution of the rock types and reflects, in part, the relative subsurface abundance of rock types from area to area. Each rock type is not a uniformly suitable host medium throughout its occurrence; indeed, some rock types appear to have unsuitable characteristics for prospective host rocks in much of the Province. The rock-type maps also provide useful supplementary information for other phases of the study. For example, the map of evaporite distribution is useful in mapping the distribution of chemical types and dissolved-solids concentration

FIGURE 5.—Outcrop areas (shaded) of fine-grained detrital rocks and their metamorphic equivalents. Only areas where thicknesses are about 150 meters (500 feet) or more are shown.

of ground water; the maps of shales are useful because these rocks impede ground-water flow and commonly have significant sorptive capacities for radionuclides.

FINE-GRAINED DETRITAL ROCKS AND THEIR METAMORPHIC EQUIVALENTS

Outcrop areas of shale, siltstone, claystone, mudstone, and their metamorphic equivalents, argillite, slate and schist, were compiled where the aggregate thickness is approximately 150 meters (500 ft) or more (fig. 5). This thickness is considered ample as a host rock for a mined repository. More detailed maps being prepared will include data about lithology, facies changes, and thickness where the information is available. Argillaceous rocks generally have little permeability and impede movement of ground water. They commonly have sorptive properties that could significantly retard radionuclide transport.

GRANITIC ROCKS

Outcrops of granite, granodiorite, and other medium- to coarse-grained crystalline plutonic rocks were compiled (fig. 6). These rocks commonly extend to

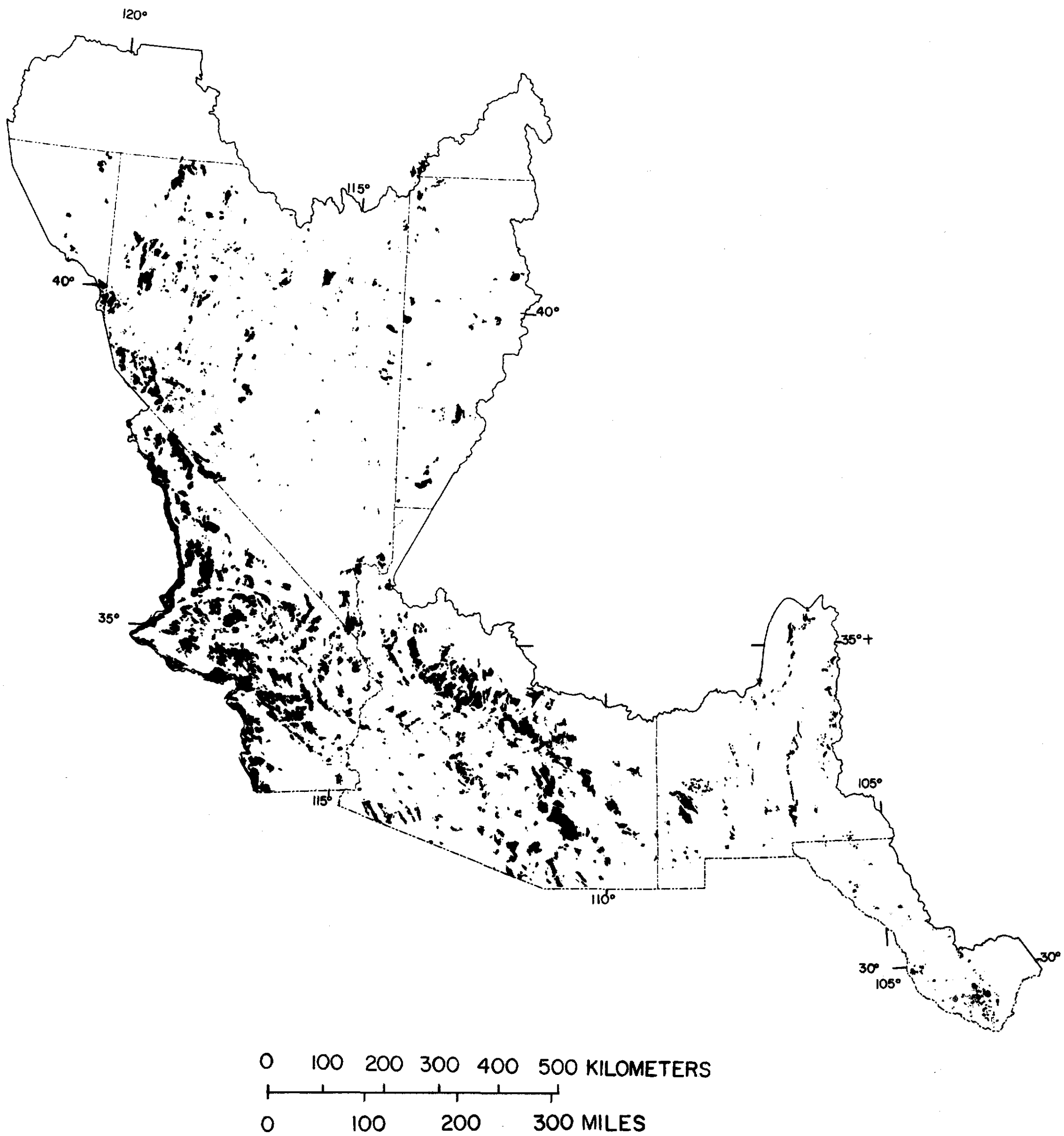


FIGURE 6.—Outcrop areas (shaded) of granitic rocks.

depths of several hundred meters or more and probably are present at depths as great as 1,000 meters (3,300 feet), the nominal maximum depth of interest for a mined repository. Exceptions to this generalization are laccolithic and other shallow bodies, such as locally occur in New Mexico, Texas, Utah, and other parts of the Basin and Range Province. Shallow intrusive rocks need to be distinguished from the larger deep-seated plutonic bodies.

The intercrystalline permeability of granitic rocks is very low. The permeability and porosity primarily are determined by density and size of openings of fractures. Fracture density in 10 test wells drilled in three areas of the United States, 7 to depths of 200 to 250 meters (660 to 820 feet) and 3 to depths of about 1 kilometer (3,300 feet) was found to decrease only slightly with depth (Seeburger and Zoback, 1982). They present no information, however, related to changes in permeability with depth. In crystalline rocks at damsites in the Front Range of Colorado at depths from a few to 100 meters (330 feet), Snow (1968a) found that the density of hydraulically significant fractures and porosity decreased with depth. Snow showed that the logarithm of permeability decreases linearly with the logarithms of depth and concluded that the decrease of permeability with depth was

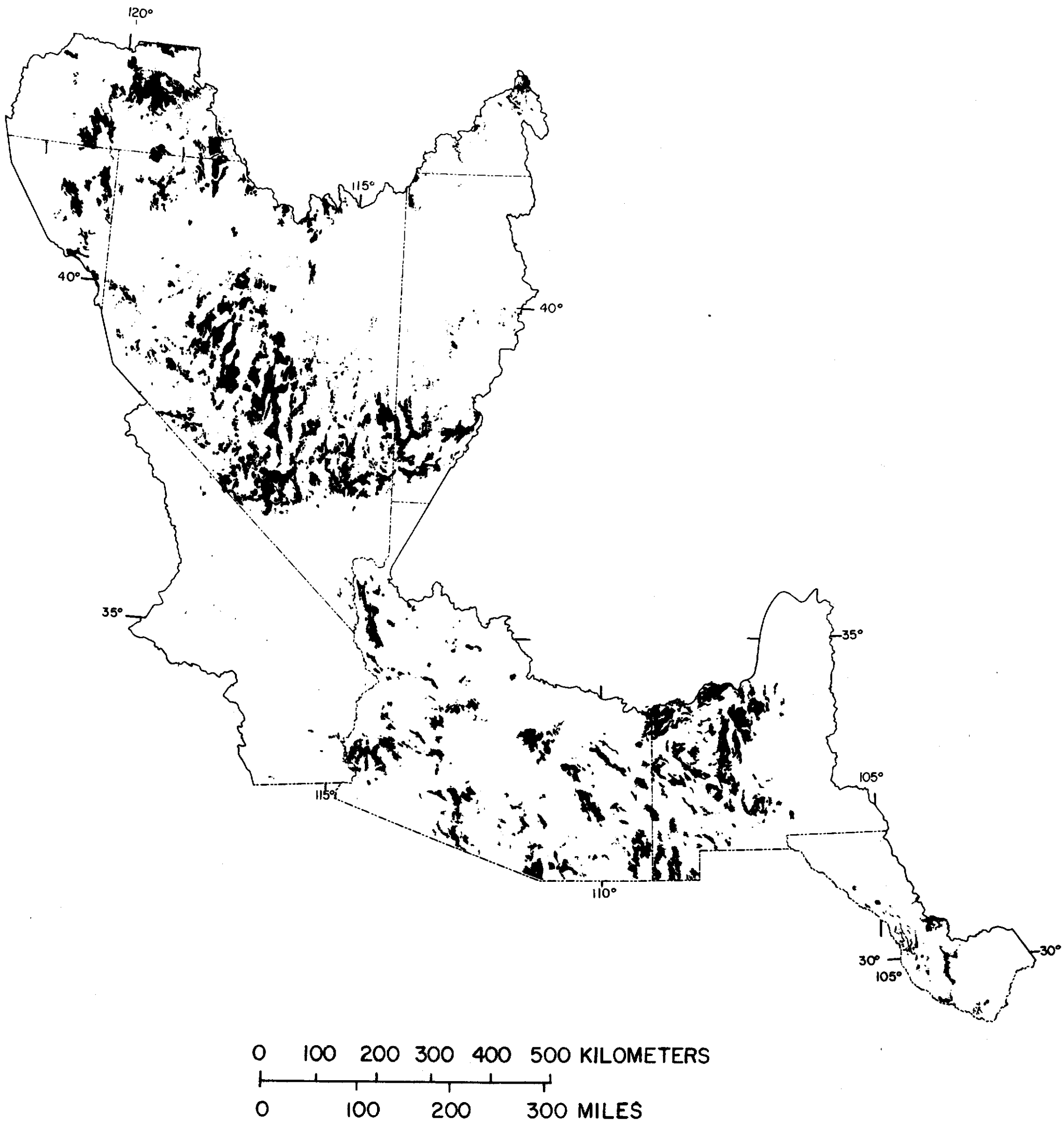


FIGURE 7.—Outcrop areas (shaded) of tuffaceous rocks.

more a result of decrease in fracture openings than decrease in fracture density (Snow, 1968b). Measurements of permeability with depth in crystalline rocks in Canada (Davison, Keys, and Paillet, 1982) show no uniform decrease in permeability with depth, although the lesser permeability values generally were found in the deeper parts of the sections. Although increased overburden pressure with depth tends to decrease the fracture openings, zones of significant permeability are found at depths as great as a few thousand meters (Keys and Sullivan, 1979; W. S. Keys, U.S. Geological Survey, oral commun., 1983).

TUFFACEOUS ROCKS

Tuffaceous rocks in the Province include welded and partly welded ash-flow tuff, ash-fall tuff and zeolitic-bedded tuff. Compilations being prepared include principally densely welded ash-flow tuffs (fig. 7), but because of the nature of the available data, the compilations also may include partly welded tuff and other associated tuffaceous rocks. Welded and zeolitic tuffs generally are permeable, and effective porosity is controlled by fractures; in friable bedded ash-fall tuff, the effective porosity and permeability are controlled by interstices (Thordarson, 1965).

Mapping of ash-flow tuffs has evolved during the past 2 decades from delineating lithologic units such as rhyolites and dacites, commonly identified as lavas, to the mapping of genetic cooling units which may (or may not) contain non-welded, partly welded, densely welded to vitrophyric tuffs, and vapor-phase zone rocks in a single mapped unit. Because of the evolving knowledge of ash-flow tuffs, it is difficult for a compiler to know how much, or even if, densely welded tuff exists in some mapped areas. To further complicate the task of compiling a map of these rocks, it has been demonstrated that in some areas of sharp relief, the continuity of cooling zones is interrupted over topographic highs. In the vicinity of most calderas, however, the existence of thick sections of moderately to densely welded tuffs is most likely. Thicknesses of intracaldera tuffs are known to attain one to two thousand meters, and similar thicknesses have been mapped in paleotopographic lows in the vicinity of extrusive centers. Because of these spatial relationships, calderas and the associated ash-flow tuffs are being compiled where information permits.

MAFIC EXTRUSIVE ROCKS

The outcrops of basalt, basaltic andesite, and other mafic extrusive rocks of pre-Quaternary age have been mapped where they are 100 meters (330 feet) or greater in thickness. Areas where mafic extrusive rocks are younger than about two million years generally are not considered prospective because of the possibility of renewed volcanism. Data compiled on mafic extrusive rocks for this study include thickness where available. Because thicknesses may change markedly within short distances, mappers of such rocks are not likely to record thicknesses at numerous locations; thus, thicknesses in many mapped areas were estimated from topographic maps. The occurrence of known mafic extrusive rocks with a thickness of about 100 meters (330 feet) or more is shown in figure 8. These rocks generally are heterogeneous and permeable by virtue of the presence of joints, fractures, bedding- and foliation-plane openings, and sedimentary interbeds. Although relatively impermeable beds are common in these rocks, the heterogeneity of basalt sequences and the common occurrence of abundant fractures mitigate against their suitability as potential host rocks in the saturated zone. The significant permeability and heterogeneity, however, are not adverse characteristics for host media in the unsaturated zone. Basalt is a potential host medium where the thickness of the unsaturated zone is sufficient to construct a repository. Fortuitously, the distribution and thickness of basalt are best known at and near the surface where basalt is best suited as a host rock in the unsaturated zone. Predictions of the occurrence of mafic extrusive rocks at a depth of 300 to 900 meters (1,000 to 3,000 feet) for a potential repository are tenuous based on surface exposures. Only where very thick sections of mafic extrusives occur or where sections are known to be down faulted is it likely to find mafic extrusive rocks at the desired repository depth.

EVAPORITES

The surface and subsurface occurrence, thickness, and inferred extent of Tertiary and older salt and anhydrite throughout the Basin and Range Province are shown in figure 9. Evaporites are both candidate repository rocks and potential barriers to movement of radionuclides. Bedded evaporites commonly contain interbedded fine silt and clay, which may be sorptive media for radionuclides, but which also contain significant moisture.

Data were collected on occurrences reported to be 100 meters (330 feet) or more thick. Because of the relative mobility and structural instability of evaporites, due largely to their ability to move plastically under lithostatic load, it commonly is difficult to determine if an evaporitic body is bedded, has thickened or thinned from its original bedded thickness, or if the body has begun to move from its original position to a position of isostatic adjustment. Because the thick evaporite units are encountered in few wells, the extent of the units has not been defined. Sections of halite greater than 100 meters (330 feet) have been penetrated by wells in Utah and Arizona.

OTHER ROCK TYPES

Locally certain rock types occur that have potential as host rocks; such rocks include laharic and mudflow breccias which occur in parts of New Mexico, Oregon, Idaho, Arizona, and Nevada. Laharic breccia occurrences have been compiled for New Mexico and Idaho where they are known to occur as thick homogeneous units. They are believed to contain a significant percentage of finely comminuted clastic particles that give the rock coherence and should enhance sorptive properties. In addition, data on shallow intrusive bodies such as rhyolite and dacite domes

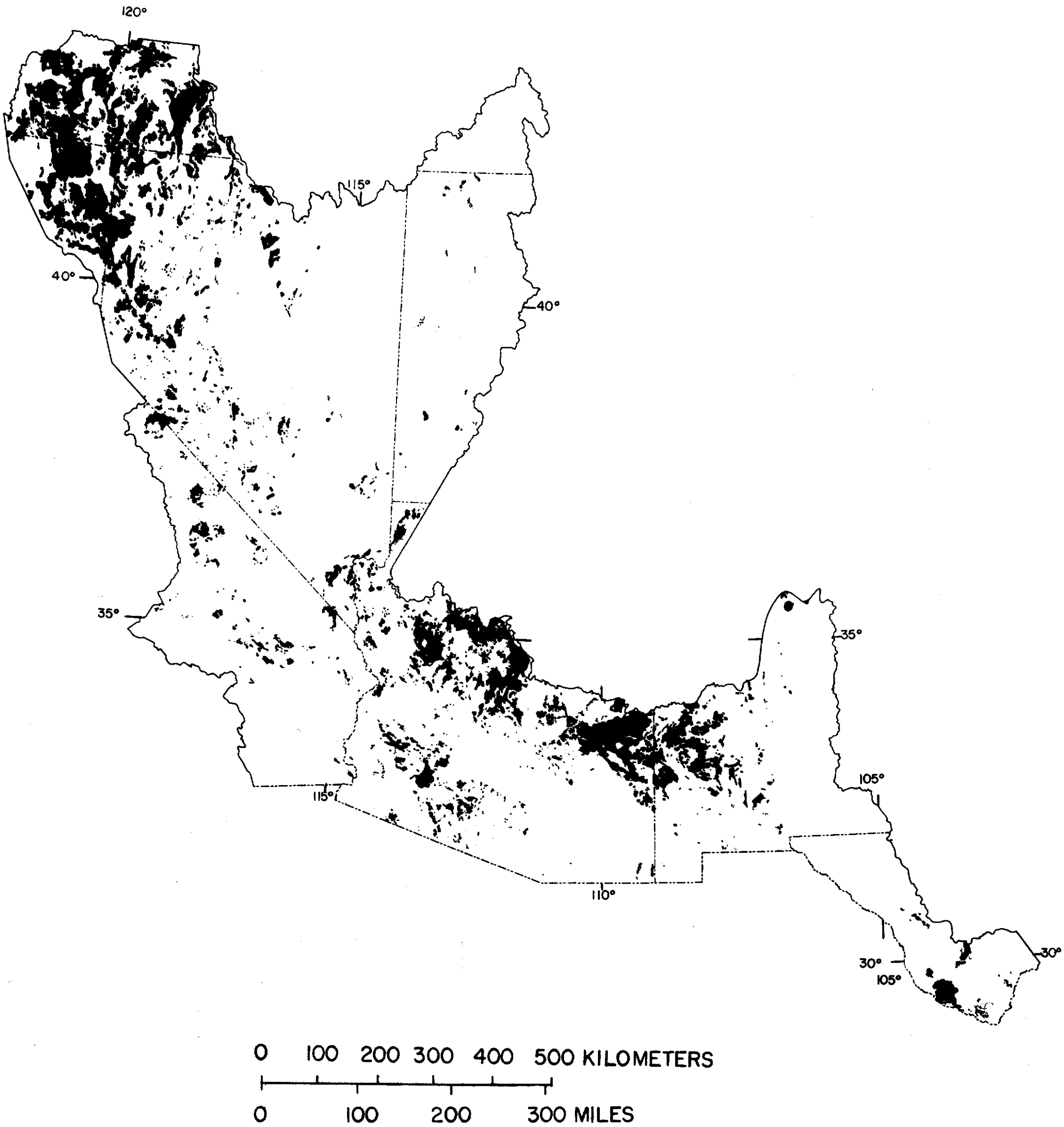


FIGURE 8.—Outcrop areas (shaded) of mafic extrusive rocks of pre-Quaternary age.

have been compiled for Texas and California. These units would have properties similar to some densely welded tuffs and may be suitable as host rocks in the unsaturated zone.

UNSATURATED MEDIA

The concept of the unsaturated zone of arid regions as an alternate environment for isolation of high-level radioactive waste was first advanced by Winograd in 1974. The concept was further examined at a site in southern Nevada by Winograd (1981). The unsaturated zone is much more than just another host rock type; it is a different hydrologic environment. The geohydrologic implications of the nature of the unsaturated environment in exploration, characterization and design of the repository and waste package are considered by Roseboom (1983).

The depth to the water table is the thickness of the unsaturated zone, except where perched ground water occurs. In basin fill and other relatively uniformly porous and permeable material, the water table is a continuous gently varying surface, and depth to water can be predicted with reasonable confidence between widely spaced data points. In the bedrock areas, the water table may be an irregular surface

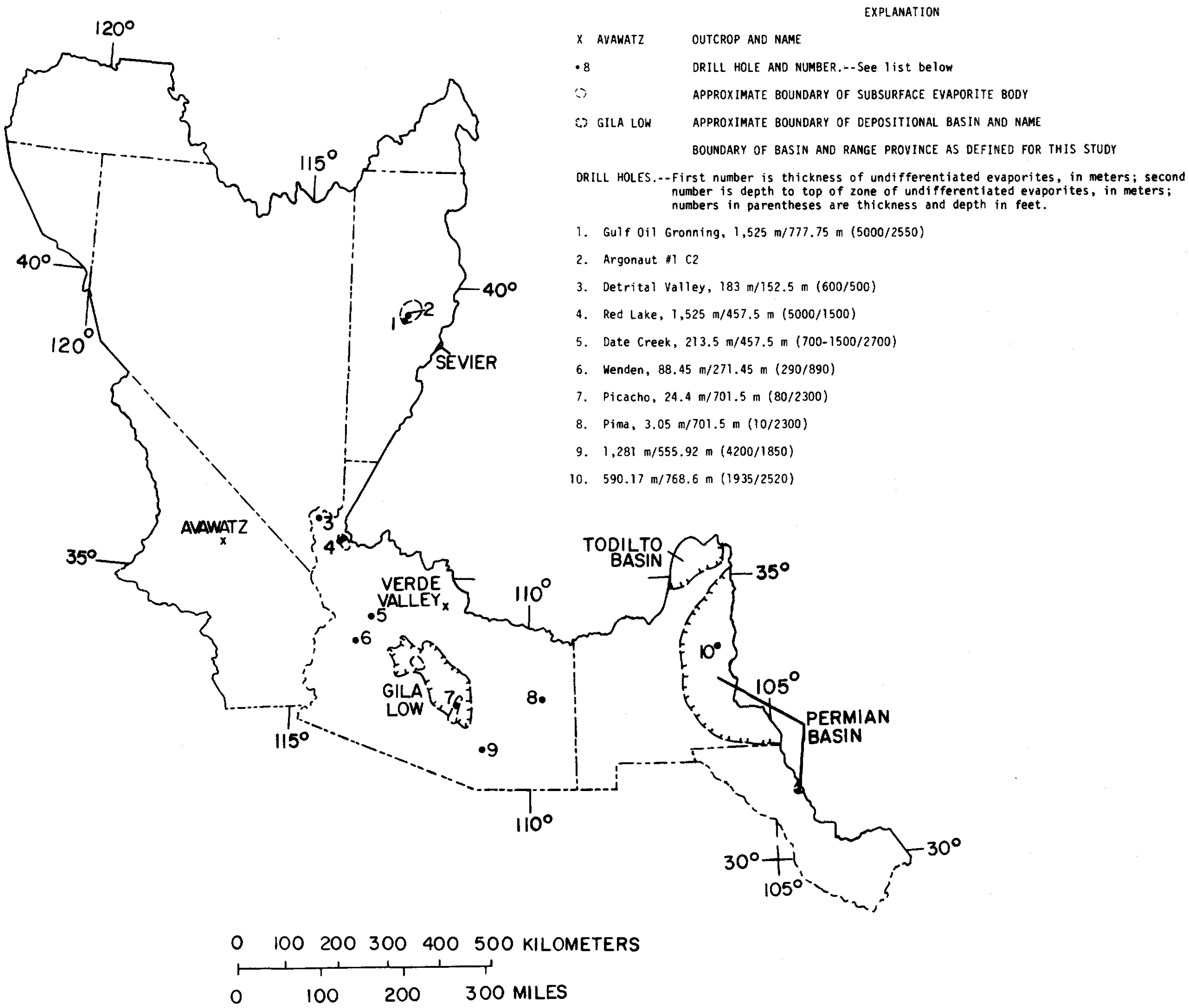


FIGURE 9.—Major surface and subsurface occurrences of Tertiary and older salt and anhydrite.

because of large differences in permeability distribution. Ground water occurs in joints or fractures in the bedrock, and these may be poorly interconnected.

Approximate areas where the unsaturated section is greater than 150 meters (500 feet) are delineated based on depth to water in wells and mine shafts, spring locations and flow rates, location of gaining reaches of streams, and estimates of geologic and hydrologic conditions in the area (fig. 10). These areas have potential for being evaluated as prospective environments for isolation of high-level radioactive waste in the unsaturated zone.

Depths to water greater than 150 meters (500 feet) commonly occur in consolidated rock beneath mountain ranges. The greatest thickness of the unsaturated zone in the Province is in south-central Nevada, where the depth to water is as great as 1,000 meters (3,300 feet). Here, the basins are underlain at depth by a permeable carbonate-rock aquifer, which is a deep ground-water drain in the region.

Many rock types may be considered as potential host media in the unsaturated zone. The suitability of rock in the unsaturated zone is more dependent on physical properties of the rock and the movement of water through the zone than on the lithologic type of the rock. In the unsaturated zone, the host medium needs to be mineable and sufficiently permeable to provide natural drainage. In some rocks drainage could be induced or enhanced by construction of water-control structures in the repository. The unsaturated zone ideally should be subject to little or no downward movement of recharge water. Rocks that may be unsuitable as a potential host media for a repository in the saturated zone, such as basin

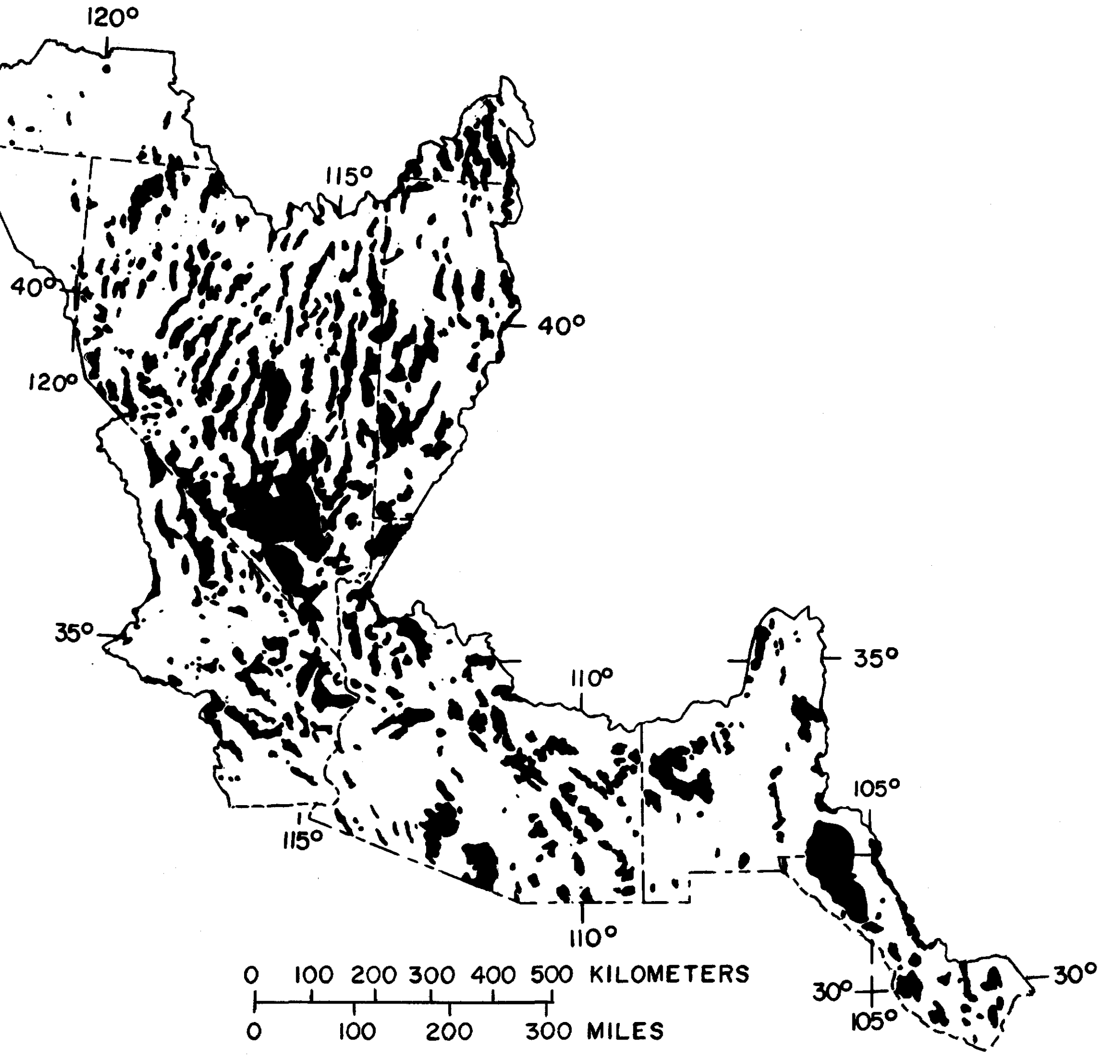


FIGURE 10.—Areas (shaded) of unsaturated thickness greater than 150 meters (500 feet).

fill, and fractured and permeable basalt and welded tuff, are potential host media in the unsaturated zone.

TECTONIC FACTORS

Tectonic stability in the Quaternary Period is considered the key to assessing the probability of future tectonic activity with regard to high-level radioactive waste disposal. Tectonic conditions in the Province are characterized by the seismic record; the distribution of Quaternary faults, volcanic features, and vertical crustal movement; and heat-flow measurements.

SEISMICITY

The record of seismicity from 1803 to 1977 was used to prepare maps showing the distribution (fig. 11) and magnitude of earthquakes in the province (Askew and Algermissen, 1983). In addition, a series of maps has been prepared by Algermissen and others (1983) showing: (1) Strain release as contoured values of cumulative energy released by the earthquakes of record (fig. 12); (2) probabilistic estimates of the horizontal velocity in rock, due to earthquake vibrations; (3) probabilistic estimates of horizontal acceleration in rock due to earthquakes; and (4) seismic-source zones of the Province based on the historic seismic record and tectonic characteristics.

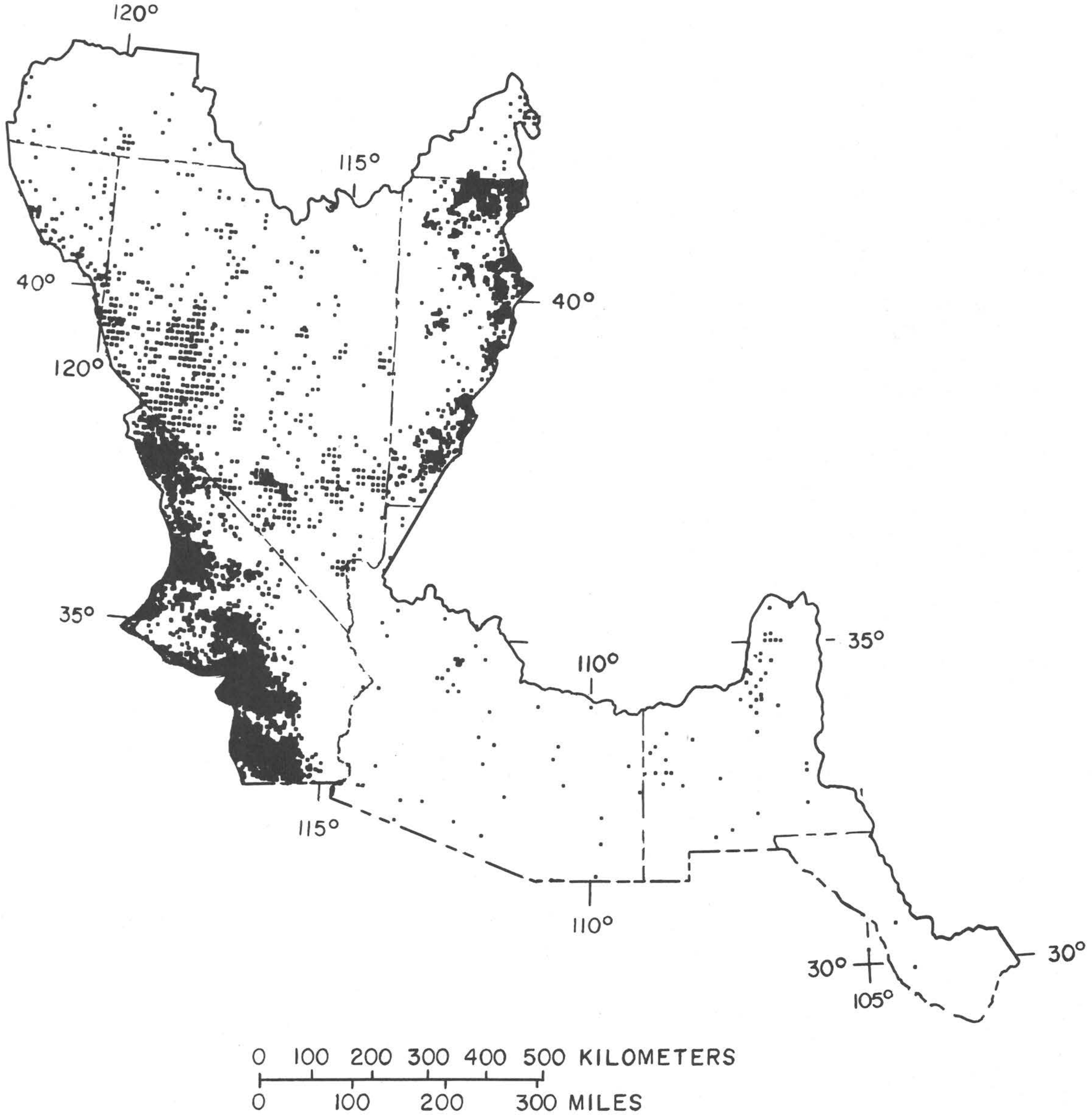


FIGURE 11.—Earthquake epicenters (dots). Modified from Askew and Algermissen, 1983.

QUATERNARY FAULTS

The map of the Basin and Range Province showing Quaternary faults, by Nakata, Wentworth, and Machette (1982), was used to prepare figure 13. This map shows several zones of relatively concentrated faulting: (1) A north- to northwest-trending zone along the western border of the Great Basin in eastern California and western Nevada; (2) a north-trending zone along the eastern border of the Great Basin in Utah and northwestern Arizona, adjacent to the Wasatch Range; and (3) a north-trending zone in the Rio Grande rift area extending from El Paso, Texas, northward through Albuquerque, New Mexico.

Fault movement tends to recur along the preexisting faults under the existing stress field. Areas having few or no Quaternary faults thus may reflect areas with little potential for faulting and with little crustal weakness. However, the apparent absence of Quaternary faults in some areas may be due to lack of detailed study; or Quaternary-fault movement may be masked by younger Quaternary deposits.

Trask (1982) discussed the problem of performance assessment of mined repositories with respect to

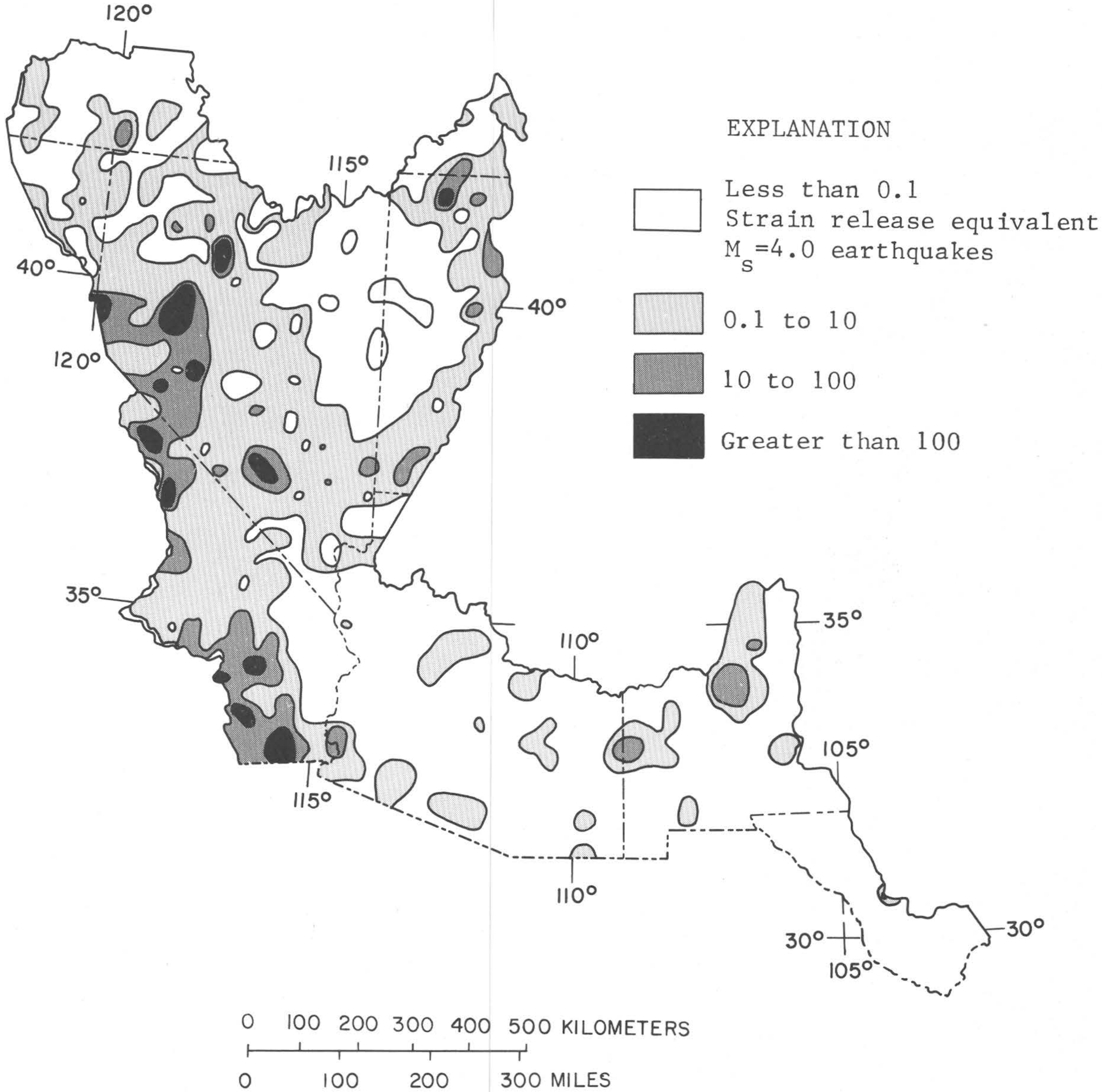


FIGURE 12.—Strain release from earthquakes. From Algermissen and others, 1983. The equivalency of a given earthquake to a M_s=4.0 earthquake is computed as 10 to the exponent ($0.75M_s=3.0$). Areas of equal strain release represent the number of equivalent M_s=4.0 earthquakes per 823 square kilometers (318 square miles) (0.25° latitude by 0.33° longitude).

fault movement. Trask has suggested an upper unit on the rate of recurrence of major movements of 8 x 10^5 events per year on active faults within the Basin and Range Province other than those near Sierra Nevada and Wasatch fronts.

LATE CENOZOIC VOLCANIC ACTIVITY

Recent compilations of late Cenozoic volcanic centers encompassing most of the States in the Basin and Range Province are now available (Luedke and Smith, 1978a, 1978b, 1981, and 1982; and Aldrich and Laughlin, 1981). The occurrence of late Cenozoic flows and eruptive centers indicates areas where analysis of volcanic hazards needs to be made in regard to repository siting.

Luedke and Smith (1978a) show local areas where there has been a distinct migration of the centers of volcanism. In general, Quaternary volcanism has been most prevalent along the east and west margins of the Great Basin and along a north-trending zone in the Rio Grande valley. Radiometric dating of

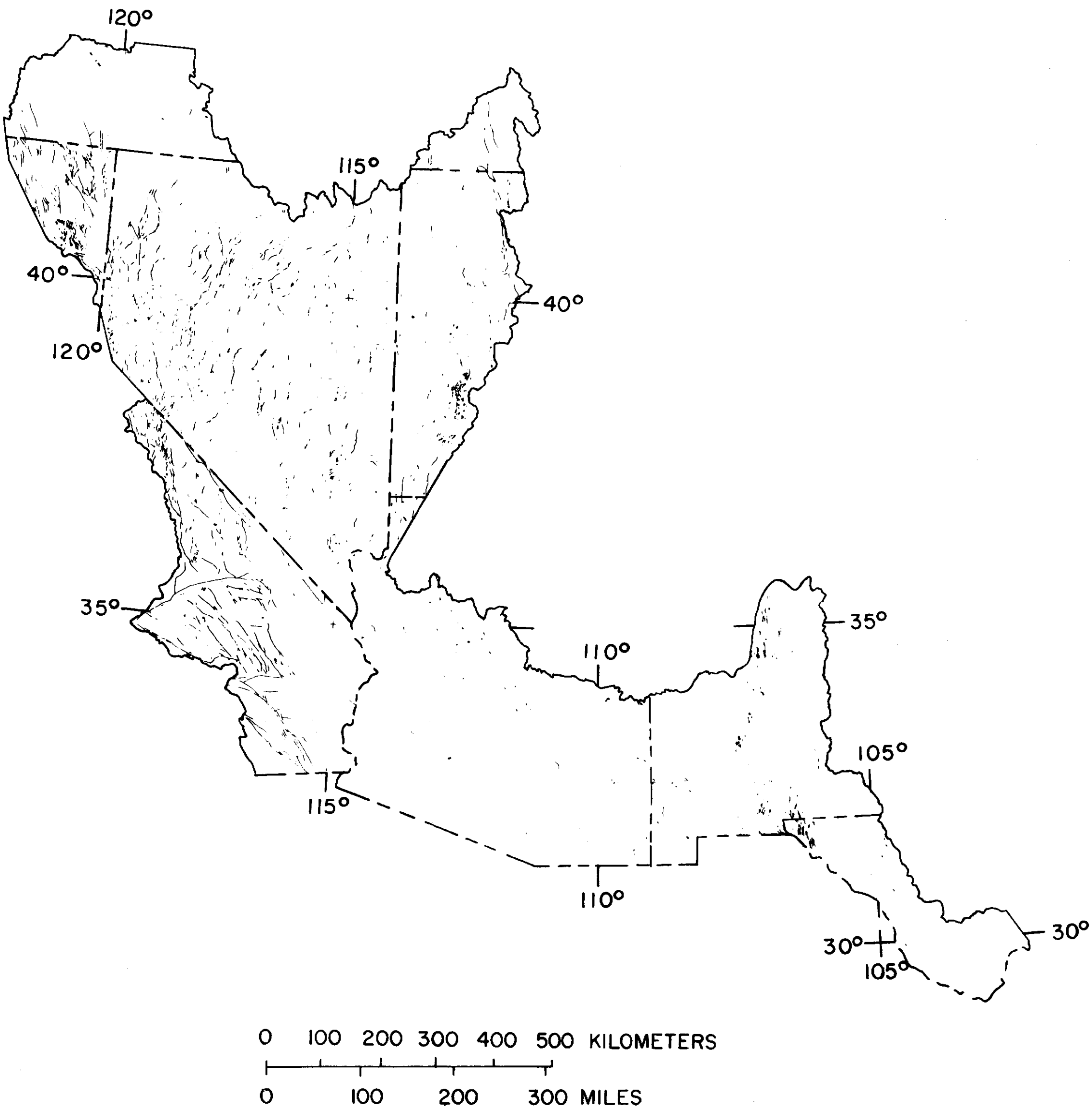


FIGURE 13.—Quaternary faults. After Nakata, Wentworth, and Machette, 1982.

volcanic features may reveal additional trends of movement of volcanic loci, such as the eastward and northeastward trends that have been documented in southern Utah and northeastern and central Arizona. A compilation of information from Luedke and Smith (1978a, 1978b, 1981, and 1982) showing volcanism for the last 5 million years is presented in figure 14.

Crowe and Carr (1980) suggest that the southern Great Basin can be zoned based on the risk of recurrence of basaltic volcanism. Ascending magma could intersect a mined repository and subsequently erupt at the surface. Crowe and others (1983) consider various aspects of the magnitude of distruption of a repository by basaltic magma in southern Nevada and the means and extent of dispersal of radioactive waste by surface eruption of the magma. They conclude that the part of the repository potentially intersected by a basaltic intrusion would be relatively small. Surface dispersal of waste by a Strombolian-type eruption would be restricted to a limited area admixed with basaltic tephra. Because most of the volcanic activity in the Basin and Range Province during the past 5 million years has involved basaltic magmas, their considerations also are applicable elsewhere in the Basin and Range.

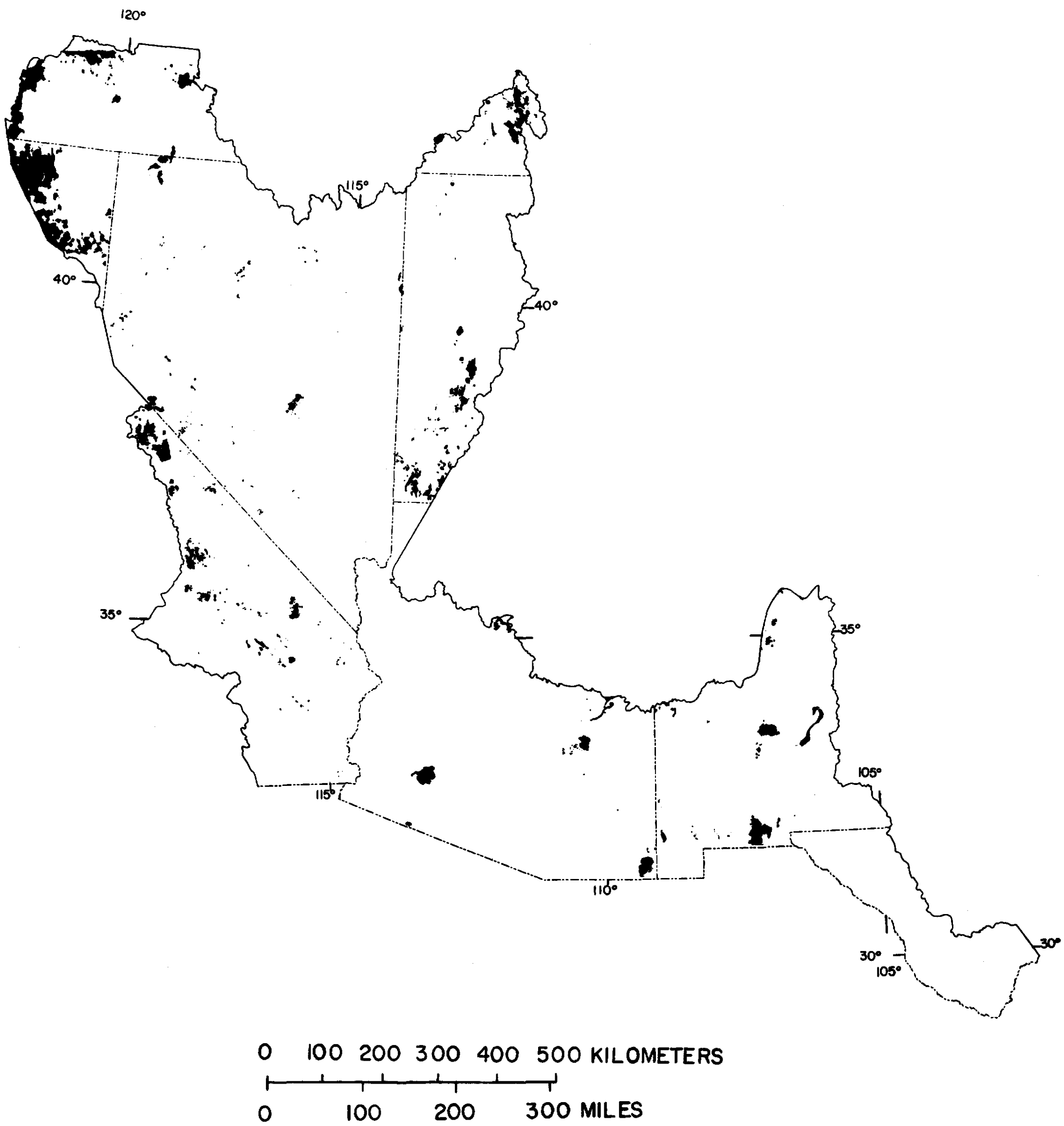


FIGURE 14.—Areas of outcrop (shaded) of volcanic rocks of late Cenozoic age. Modified from Luedke and Smith, 1978a, 1978b, 1981, and 1982.

QUATERNARY VERTICAL CRUSTAL MOVEMENT

Gable and Hatton (1980) compiled a series of four maps showing the amount of vertical crustal movement in the Basin and Range Province since the beginning of the Quaternary Period. These maps generally are useful in identifying regions of potentially rapid rates of uplift where erosion could decrease the thickness of cover over a repository. If a prospective region is studied further, additional data on subsidence or uplift would be appropriate. In addition, certain areas of uplift or bulging might indicate the shallow invasion by magma or tectonic instability. Rates of uplift in the Province shown in figure 15 are based on the following data from Gable and Hatton (1980): (1) Geology, geomorphology, and radiocarbon dating; and (2) geodetic leveling.

HEAT FLOW

Heat-flow measurements are an attempt to quantify the amount of the Earth's heat that is being transferred to the atmosphere at a given point. Heat flow is determined by measuring the geothermal gradient

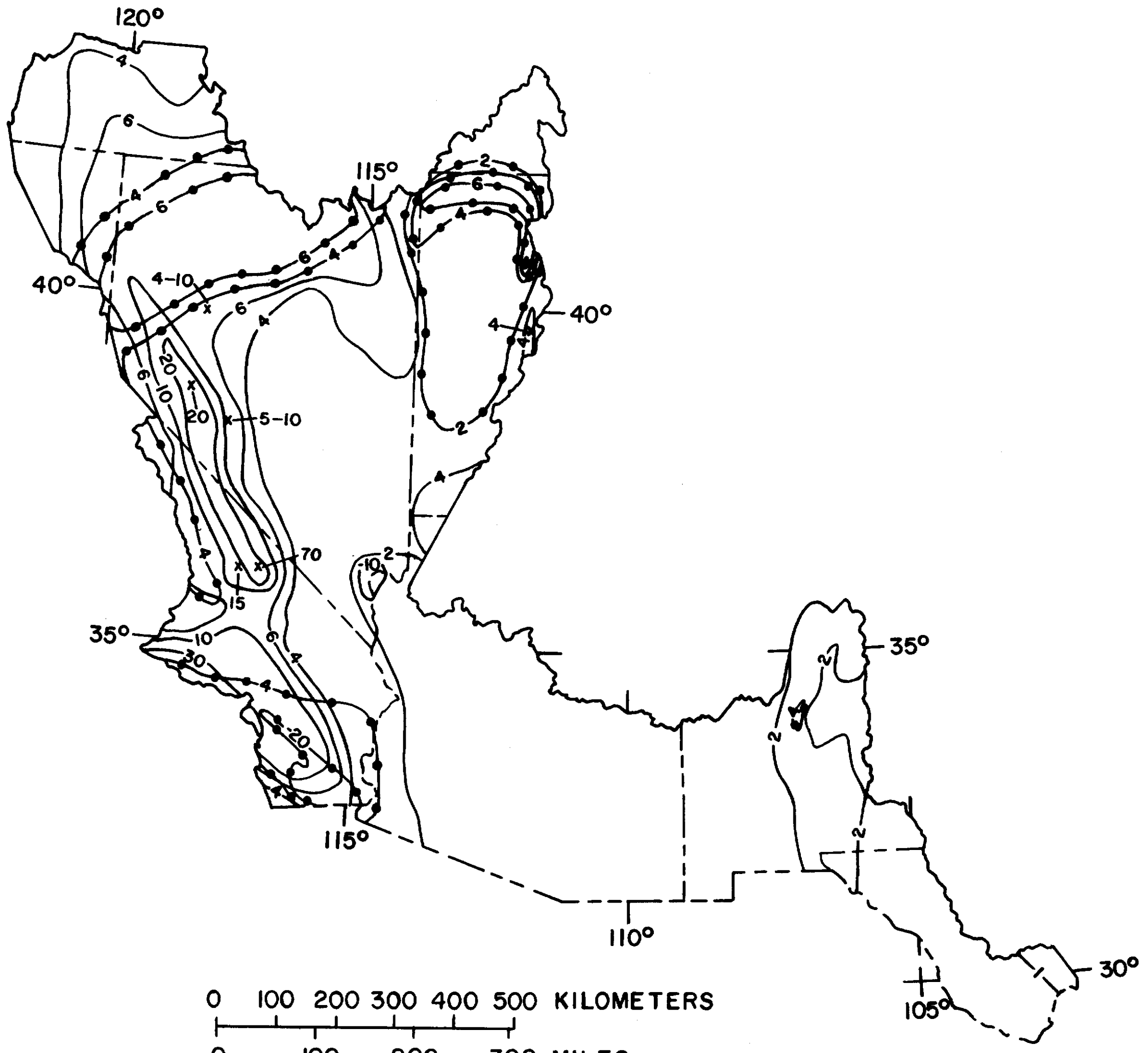


FIGURE 15.—Rates of vertical crustal movement. Solid lines are in meters per 10,000 years based on geology, geomorphology, and radiocarbon dates. Solid lines with dots are in millimeters per year based on geodetic-leveling data. Modified from Gable and Hatton, 1980.

(rate of temperature change with depth) in drill holes and measuring the thermal conductivity of rock samples from the drill hole. The standard measurement unit is called the heat flow unit (HFU). One HFU is equivalent to 1×10^{6} calories per square centimeter per second.

A map of heat flow (fig. 16) has been compiled for the Basin and Range Province by J. H. Sass (U.S. Geological Survey, written commun., 1982) revising the map of heat flow for the conterminous United States (Sass and others, 1976). The mean value of 650 point measurements is 2.1 HFU, although the points are not evenly distributed.

Within the Province, areas with greater than average heat flow include: (1) The Battle Mountain high area of northern Nevada and adjacent parts of Idaho, Oregon, and Utah, (2) the Salton Trough area of southern California, and (3) the Rio Grande rift area of southern New Mexico. Other areas with greater than average heat flow occur along the eastern margin of the Province in Utah, along the western boundary of the Province in California, Nevada, and Oregon, and at localities in eastern Nevada and southcentral Arizona. The greater than average heat-flow areas of the Salton Trough, Rio Grande rift and the eastern and western margins of the Province are in tectonically active areas as evidenced by Quaternary faulting, seismicity, and locally by late Cenozoic volcanic activity. In contrast, the Battle Mountain high is relatively quiet tectonically,

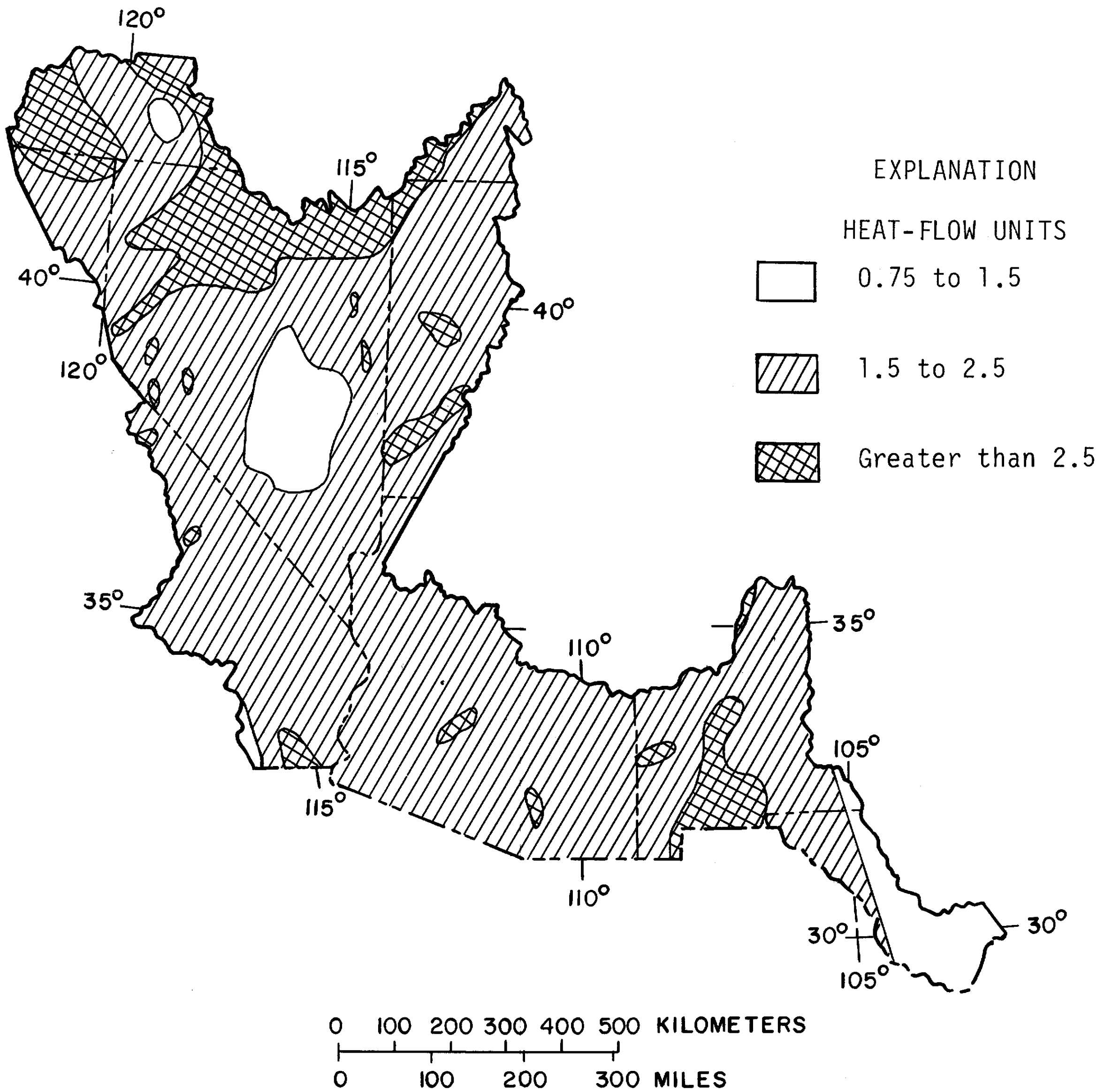


FIGURE 16.—Heat flow. One heat-flow unit is equivalent to 1 x 10^{-6} calories per square centimeter per second. Modified by J. H. Sass (U.S. Geological Survey, written commun., 1982) from Sass and others (1976).

but was recently found to have a thin crust (23 to 35 kilometers or 14 to 22 miles thick), at least 20 kilometers (12 miles) thinner than in central Nevada (Stauber, 1983).

Three areas within the Province have heat flow that is markedly less than the average for the Province. The Eureka low in central Nevada, a part of the Mojave Desert in southern California, part of the Trans-Pecos region of Texas and New Mexico, and a smaller area in south-central Oregon have heat-flow values that are less than 1.5 HFU. These heat-flow areas may be related to slow transfer of heat (low reduced heat flow) or to convective redistribution of heat by ground-water flow.

GROUND-WATER HYDROLOGY

Characterization of the ground-water hydrology of the Province is based principally on information compiled on ground-water-level elevation, depth to ground-water below the land surface, flow and temperature of springs, ground-water withdrawal, perennial surface-water features, chemical quality of ground water, and information on the geology of

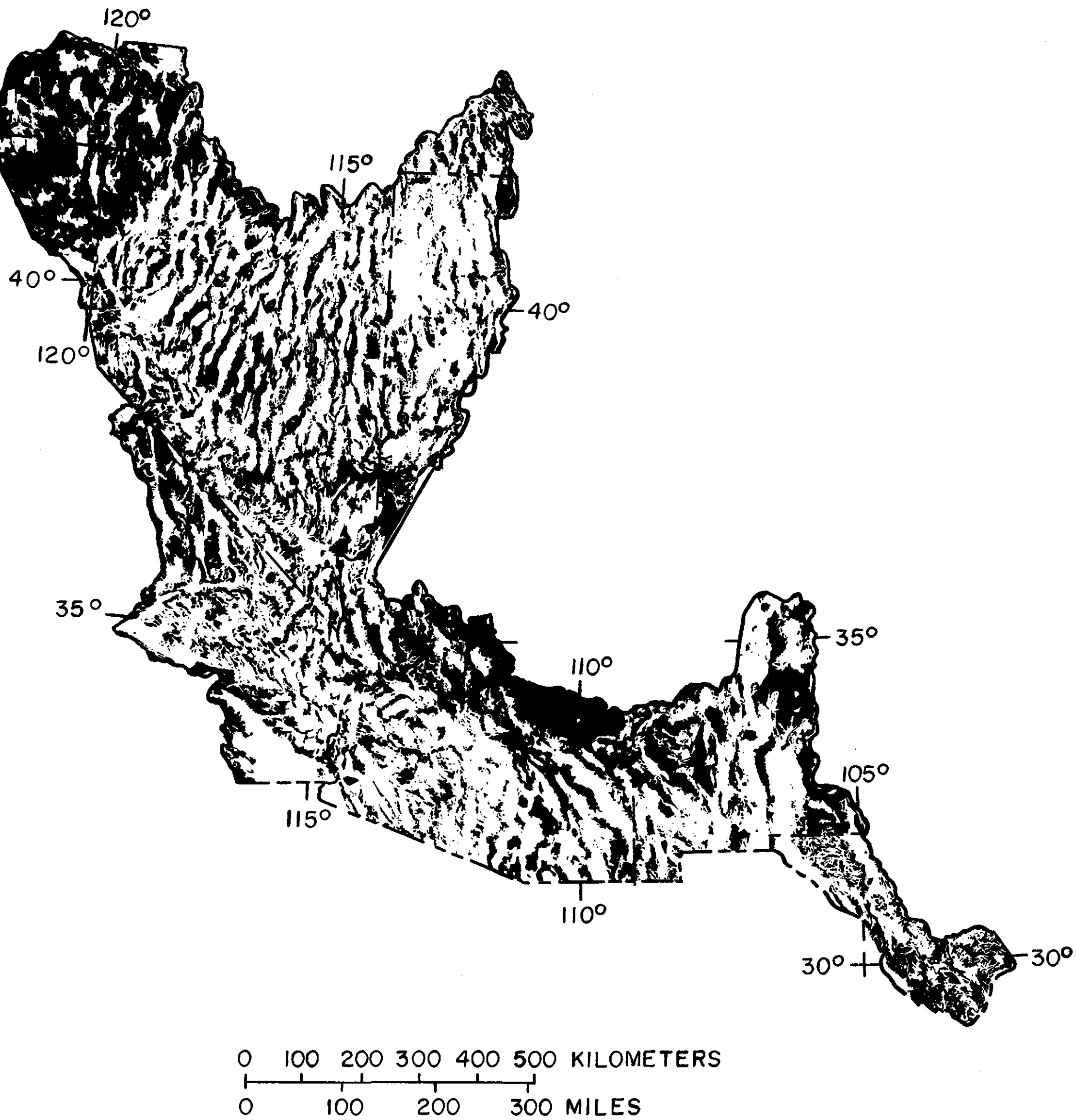


FIGURE 17.—Areas of bedrock (shaded) and basin fill (unshaded).

the Province and hydrologic properties of the rocks.

The most obvious geologic distinction that has hydrologic significance in the Province is the difference in properties of the basin-fill deposits and consolidated rocks (fig. 17). Basin-fill deposits vary in lithology and include evaporites, clays, silts, sands, and gravels. The older deposits of the basin date the time of formation of the basin and range structures in the middle Tertiary Period; they commonly are more consolidated and cemented and less permeable than the more recent deposits. Though grain size of deposits varies considerably vertically as well as laterally because of the varying rates of uplift and erosion of the bounding mountain blocks in many basins, a consistent change in texture commonly occurs from coarse at the margins to fine sediments in the central parts of the basins. Evaporites typically occur in the central parts of the basins and include carbonates and simple to complex salts that may be interbedded with silts and clays. The thickness of the evaporite and fine-grained sequence in basins is as great as 3,000 meters (10,000 feet) (Peirce, 1981; Smith and others, 1983). Although permeability of basin-fill deposits varies greatly, basin fill constitutes the principal aquifers of the Province, yielding water supplies to wells for many uses.

The consolidated rocks in the Province vary in age (Precambrian to Quaternary) and rock types (igneous intrusive and extrusive rocks, sedimentary carbonate rocks, shale, sandstone, and metamorphic schist, gneiss, and phyllite), and commonly have relatively little permeability. Permeability in consolidated rock commonly is dependent on the presence of joints and fractures. Solution along joints and fractures has increased the permeability of some carbonate rocks.

Hydraulic head is the single most definitive parameter in determining flow within a system and in delineating system boundaries. However, the interpretation of hydraulic-head distribution needs to recognize the three-dimensional aspects of the parameter as affected by sources (recharge) and sinks (discharge), fluid-density variations, and the permeability of the materials comprising the flow system. Interpretation of hydraulic head can be aided by the use of generalized models of flow showing equipotential and flow lines in hypothetical sections (fig. 18). The hypothetical sections are drawn through several topographic basins and ranges. Recharge occurs in the ranges; discharge occurs in the basins. A flow net in a system of uniform permeability is depicted in figure 18A; a flow net in a system with a more permeable layer at depth is depicted in figure 18B.

Conditions that can be identified from these sections include:

1. The vertical component of hydraulic gradient is downward beneath areas of recharge;
2. the vertical component of hydraulic gradient is upward beneath areas of discharge;
3. the vertical component of hydraulic gradient is zero in areas of horizontal flow;
4. ground-water divides on the surface of the zone of saturation may or may not extend vertically downward to the base of the flow system. The resulting pattern is small, subsidiary flow system at shallow depth, underlain by regional transbasin flow; and
5. flow at depth, especially in zones of greater permeability (regional flow systems), may extend beyond boundaries of shallow, subsidiary flow system. Regional flow is less probable in areas where less permeable rocks occur at depth.

Although hydraulic head is the most definitive parameter in defining flow system, other data were used in addition to hydraulic head in defining flow systems. These include indirect evidence of recharge and discharge of ground water, chemical quality of ground water, and data for water-budget components of the flow system.

The Province was divided into ground-water flow units based primarily on ground-water level altitude, discharge areas, and perennial surface-water features (fig. 19). The boundaries of ground-water flow units were defined on the basis of ground-water divides, ground-water flow lines, and surface streams that receive ground-water discharge. A ground-water unit is defined by the water table in a manner analogous to that by which surface-drainage basins are defined by the topography. Not all topographic divides are coincident with water-table divides; however, where water-level data were insufficient to completely define the boundaries of the units, ground-water divides and the directions of ground-water gradients were assumed to be reflected by the surface topography. Each ground-water unit receives ground-water recharge and contains one or more discharge areas. Because ground-water units were defined by water levels in relatively shallow wells and other observations of surface features, such as the occurrence of springs, playas, lakes, and streams, the ground-water units reflect relatively shallow flow of ground water beneath the water table. The ground-water units do not reflect deep, regional flow which may occur beneath ground-water units in some areas. Deep, regional flow, known or inferred, beneath ground-water unit boundaries will be shown in the ground-water unit maps for each State that are being prepared.

Many ground-water studies in the Basin and Range Province have provided evidence that ground-water flow may occur in deep aquifers between ground-water units. Paleozoic carbonate rocks at depth in southern and eastern Nevada and western Utah are believed to constitute large regional flow systems. The flow system in southern Nevada has been described by Winograd and Thordarson (1975); the flow system in western Utah has been identified by Gates and Kruer (1981). Flow beneath adjacent ground-water units also has been inferred by many studies in Nevada and Utah based on water-budget calculations. Price and Eakin (1974) summarize much of the information on interbasin flow of ground water in the Great Basin.

GROUND-WATER QUALITY

Chemical analyses of ground water were used in characterization of the Province to describe the spatial distribution of chemical properties of ground

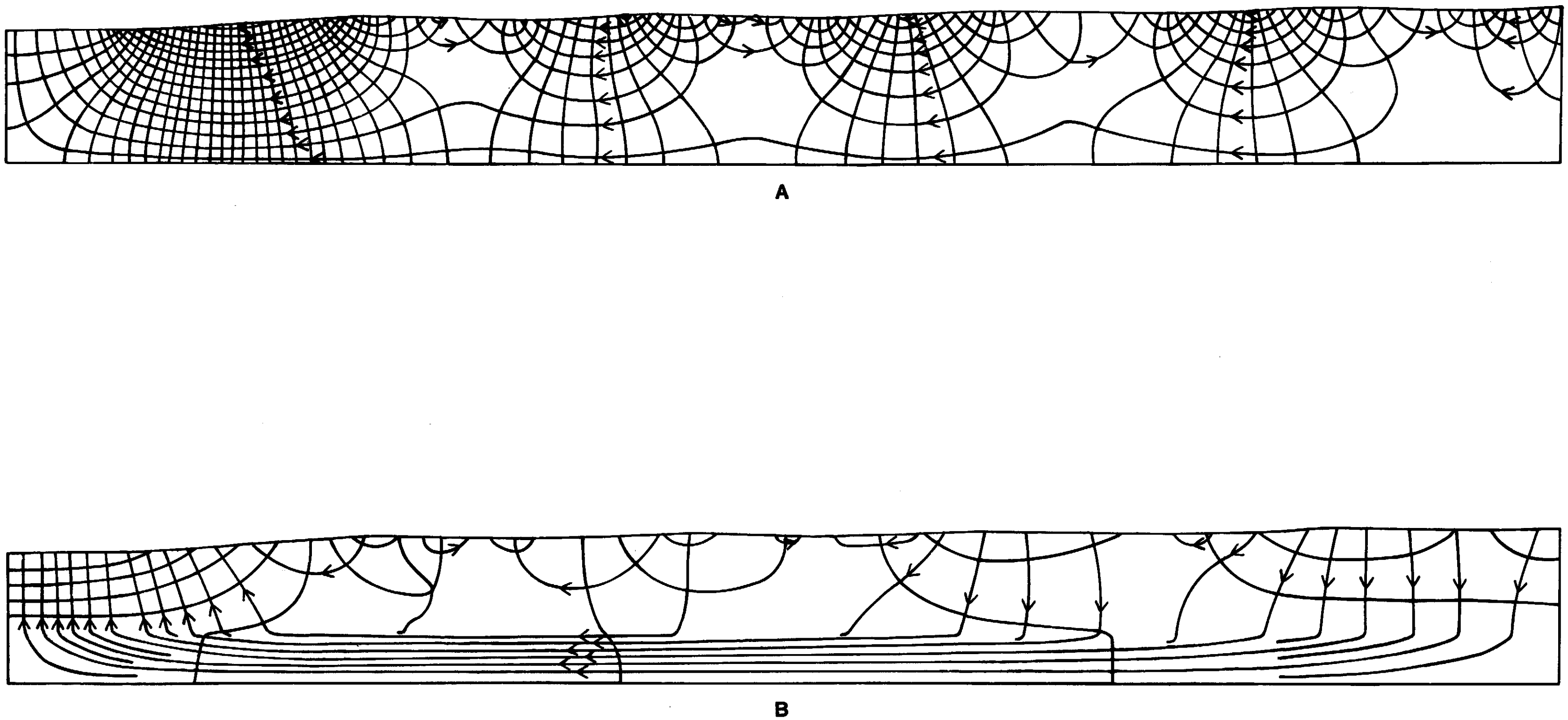


FIGURE 18.—Diagrammatic sections showing lines of equal hydraulic head (solid) and flow lines (solid with arrows). A, hydraulic head and flow lines in an isotropic aquifer; B, hydraulic head and flow lines in a two-layered aquifer in which the lower part of the aquifer is 10 times as permeable as upper part of the aquifer.

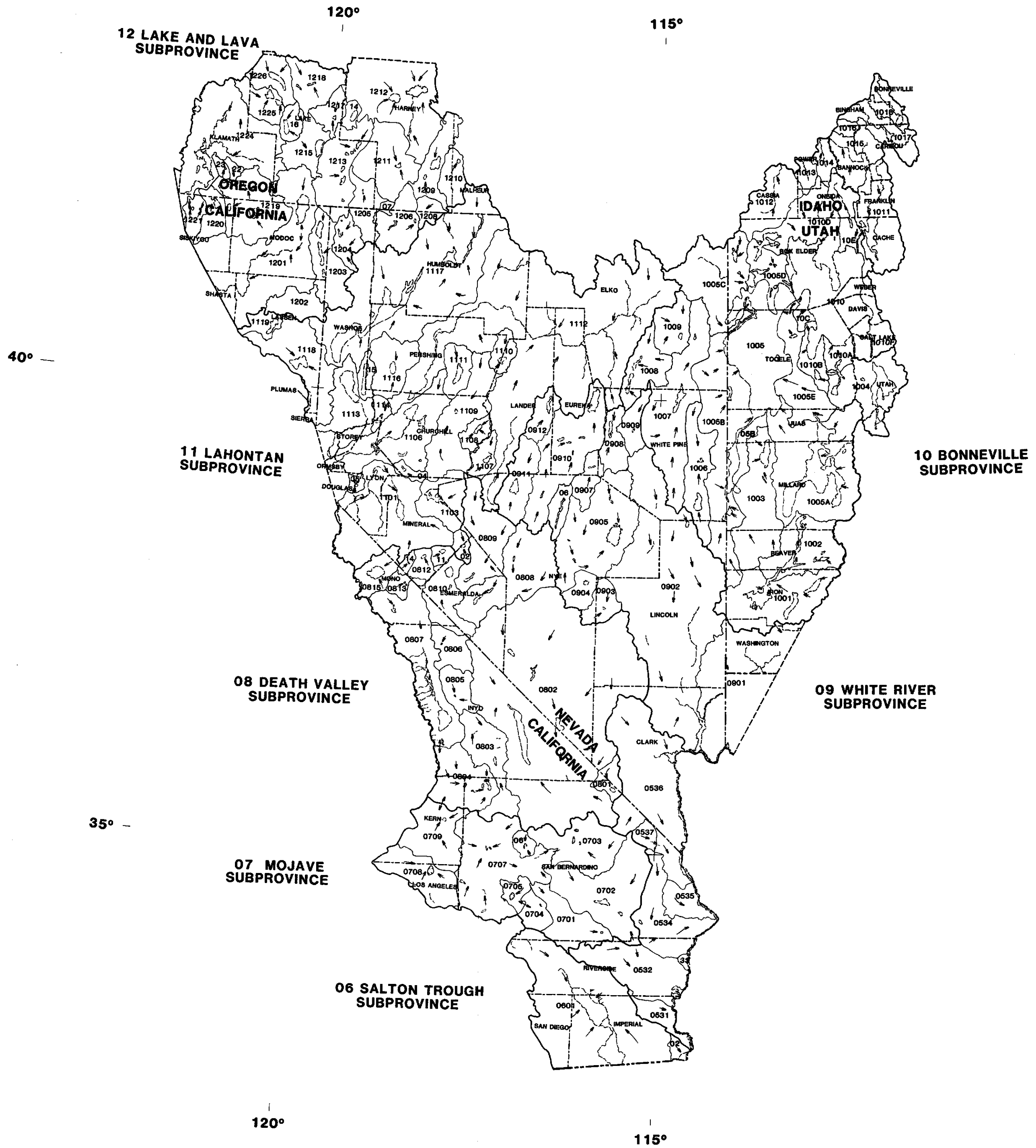


FIGURE 19 (above and facing page).—Subprovinces and ground-water units. Boundary of the Province is dashed where not coincident with a ground-water flow unit boundary. Ground-water units are numbered; the first two digits refer to the subprovince; the second two digits are unique for each ground-water unit within the subprovince. Arrows indicate the general direction of ground-water flow at the water table; shaded areas outlined by closed dashed lines are natural discharge areas; dashed lines are stream reaches that receive ground-water discharge; areas outlined by hachured lines are areas of withdrawal by wells, or, in unit 0104 in Texas, a natural depression in the water table (noted by *).

water, and as an aid in understanding the chemical evolution of the water and the flow systems.

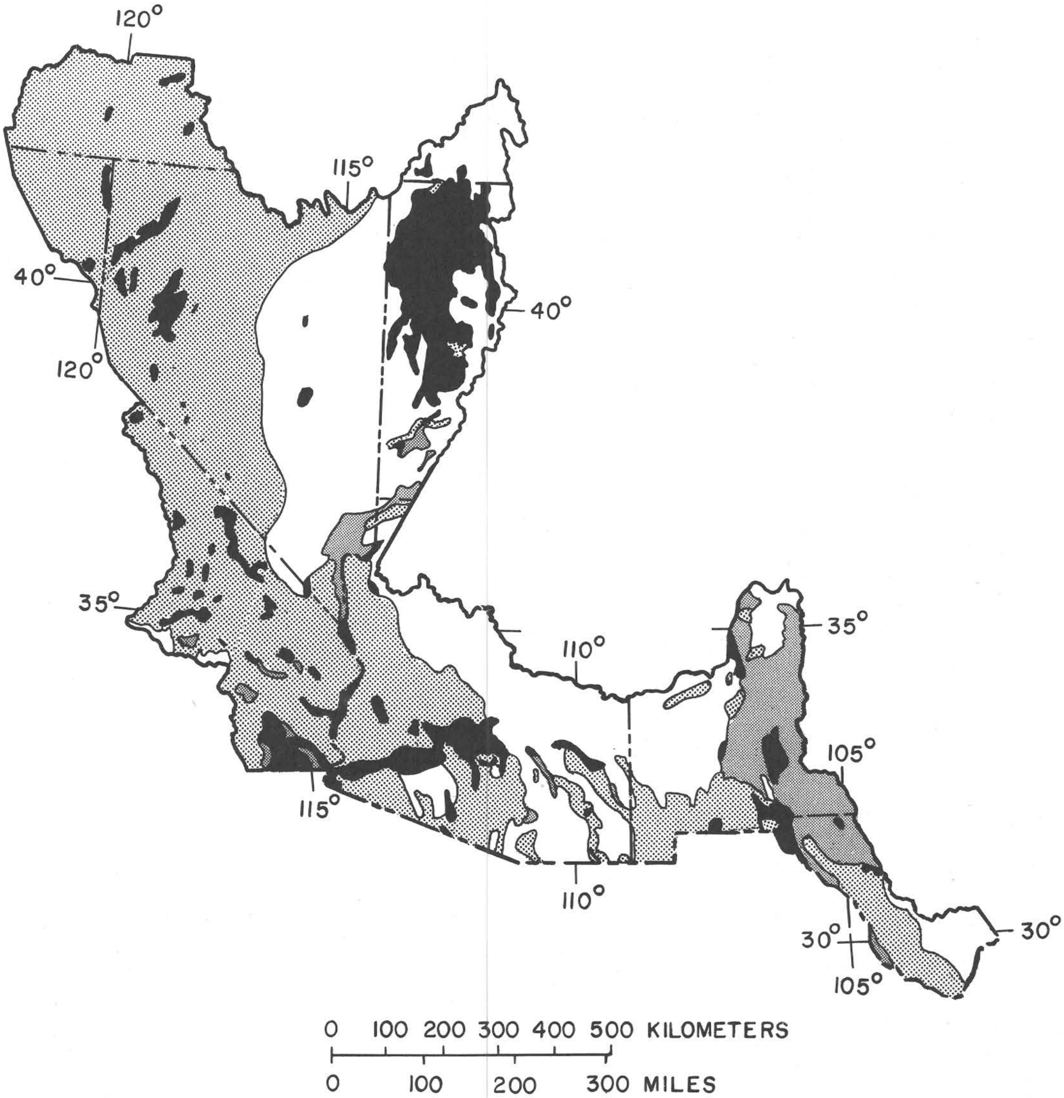
The water quality in the Basin and Range Province is shown in figure 20 as classified by major cations and anions and in figure 21 as classified by content of dissolved-solid concentration.

A principal ion (cation or anion) is one which exceeds the other ions (cations or anions) by 10 percent of the total ions expressed in milliequivalents per liter. Two or three ions may be principal ions in a water in which the milliequivalents per liter of the predominant constituents are within 10 percent.

Waters of Type I, calcium, magnesium, bicarbonate waters, commonly have dissolved-solids concentrations that are less than 500 mg/L and rarely exceed 1,000 mg/L. These waters underlie about 30 percent of the Province and occur in areas where the geologic materials have a greater abundance of calcium and magnesium than sodium. Such materials include carbonate rocks, mafic and intermediate lava flows, extrusive rocks, and silicic intrusive and metamorphic rocks that have a significant content of ferromagnesian minerals. Hydrologically this type of water occurs in the upgradient, recharge parts of the flow systems.

Waters of Type II are principally sodium bicarbonate waters; however, calcium and magnesium may also be major cations. The dissolved-solids concentration, although as much as 2,000 mg/L, is generally less than 1,000 mg/L and commonly less than 500 mg/L. Water of Type II underlies about 40 percent of the Province and originates from: (1) Solution of sodium-enriched materials, especially glassy volcanic rocks, and also such rocks as granite, syenite, and crystalline silicic volcanics; (2) ion exchange, in which calcium and magnesium in ground water are exchanged for sodium in clays; and (3) increased concentration of sodium by precipitation of less soluble salts of calcium and magnesium.

Waters of Type III, sulfate waters, underlie about 10 percent of the Province. Sulfate waters, commonly a calcium sulfate type, originate from solution of rocks containing anhydrite and gypsum, as in New Mexico east of the Rio Grande and in southern Nevada. Sulfate enrichment also may occur by



EXPLANATION

GROUND-WATER QUALITY TYPES

- Type I---Calcium or magnesium are principal cations; bicarbonate is the principal anion.
- Type II--Sodium is a principal cation; bicarbonate is the principal anion.
- Type III-Calcium, magnesium, or sodium is a principal cation; sulfate is a principal anion; chloride is not a principal anion.
- Type IV--Calcium, magnesium, or sodium is a principal cation; chloride is a principal anion.

FIGURE 20.—Groundwater quality types.

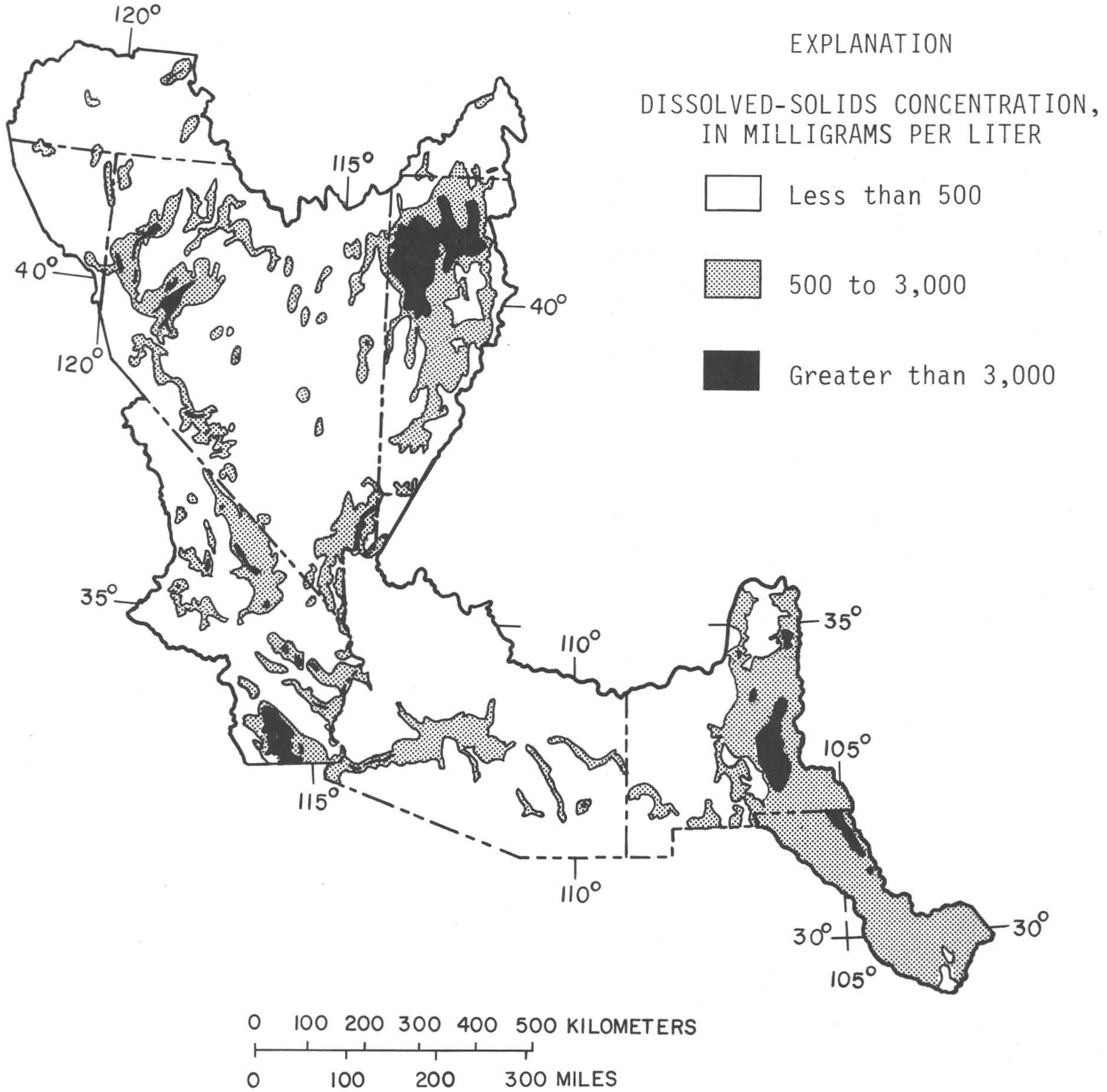


FIGURE 21.—Dissolved-solids concentration in ground water.

evaporation. The dissolved-solids concentration of these waters generally ranges from 1,500 to 4,000 mg/L. Water containing significant sulfate occurs in some playas where sulfate is concentrated by evapotranspiration of ground water. In this environment, sodium commonly is increased relative to calcium and magnesium by precipitation of the less soluble salts of calcium and magnesium.

Waters of Type IV are chloride waters and underlie about 17 percent of the Province. Bicarbonate and sulfate also may be present in major concentrations. The principal cation commonly is sodium. These waters may originate by solution of halite or by concentration of the soluble salts by evaporation of water and deposition of less soluble salts such as calcium and magnesium bicarbonates. Chloride waters are common in playas and concentrations of dissolved solids range from 1,500 to more than 300,000 mg/L.

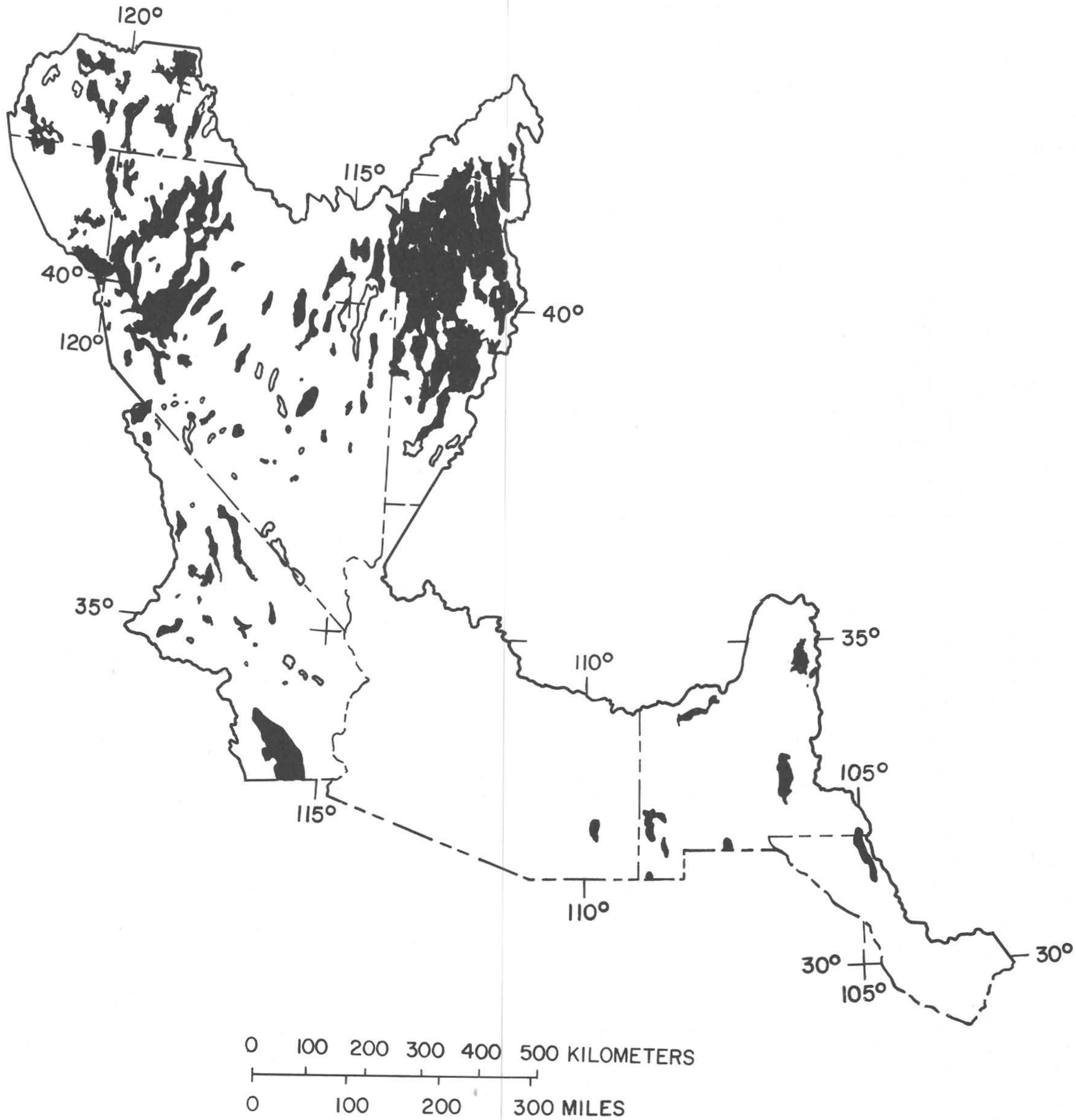


FIGURE 22.—Pleistocene lakes (shaded) and marshes (open).

PLEISTOCENE HYDROLOGIC FEATURES

Geologic evidence for the existence of approximately 100 lakes and marshes (fig. 22) indicates that pluvial climates existed at times during the Pleistocene Epoch. Investigators have presented evidence based on orbital variations of the Earth to support the theory that climatic conditions similar to those of the Pleistocene may recur within the next 10 to 20 thousand years (Imbrie and Imbrie, 1980). A recurrence of a pluvial climate would affect the ground-water flow system. The climatic change would be accompanied by increased recharge, increased ground-water flow, regional water-level rises, and adjustments in hydraulic gradients to these changes. The most significant changes would be the rise in ground-water level at the pluvial lakes and in the flow system because of the increase in recharge and the shortening of ground-water flow paths from the ground-water divides to the natural discharge points.

Shorelines of Pleistocene water bodies have been identified from geologic evidence. The elevations of the Pleistocene lake levels are indicators of the elevation of the water table at that time. Few of the

Pleistocene lake basins are occupied by lakes today. However, beneath many of the basins the modern water table is within 10 meters (30 feet) of the surface. The difference between maximum Pleistocene lake elevation and the present ground-water level is a measure of the possible future change in ground-water level at that location during pluvial conditions. Several investigators have used data from the Pleistocene lake basins to estimate the climate during the time of maximum lake elevation (Leopold, 1951; Snyder and Langbein, 1962; Mifflin and Wheat, 1979; Brakenridge, 1978). Though the analyses differ in degree of sophistication and in detail and in estimates of magnitudes, the general consensus of the studies is that a cooler and wetter climate existed during Pleistocene pluvial times.

REFERENCES CITED

Aldrich, M. J., and Laughlin, A. W., 1981, Age and location of volcanic centers ≤ 3.0 M.Y. old in Arizona, New Mexico, and the Trans-Pecos area of West Texas: Los Alamos, New Mexico, Los Alamos National Laboratory Map LA-8812-MAP, Revised, UC-11, scale 1:1,000,000.

Algermissen, S. T., Askew, Bonny, Thenhaus, P. C., Perkins, D. M., Hanson, S. L., and Bander, B. L., 1983, Seismic energy release and hazard estimation in the Basin and Range Province: U.S. Geological Survey Open-File Report 83-358, 13 p.

Askew, Bonny, and Algermissen, S. T., 1983, An earthquake catalog for the Basin and Range Province, 1803-1977: U.S. Geological Survey Open-File Report 83-86, 21 p.

Bedinger, M. S., Sargent, K. A., and Brady, B. T., 1983, Geologic and hydrologic characterization and evaluation of the Basin and Range Province relative to the disposal of high-level radioactive wastes, Part III—Geologic and hydrologic evaluation: U.S. Geological Survey Circular 904-C, 27 p., 1985.

Bedinger, M. S., Sargent, K. A., and Reed, J. E., 1983, Geologic and hydrologic characterization and evaluation of the Basin and Range Province relative to the disposal of high-level radioactive wastes, Part I—Introduction and guidelines: U.S. Geological Survey Circular 904-A, 16 p., 1984.

Berry, G. W., Grim, P. J., and Ikelman, J. A., compilers, 1980, Thermal springs list for the United States: National Oceanic and Atmospheric Administration Key to Geophysical Records Documentation no. 12, 59 p.

Brakenridge, G. R., 1978, Evidence for a cold, dry, full-glacial climate in the American southwest: Quaternary Research, v. 9, no. 1, p. 22-40.

Busby, M. W., 1965, Annual runoff in the conterminous United States: U.S. Geological Survey Hydrologic Investigations Atlas HA-212, scale 1:7,500,000.

Crowe, B. M., and Carr, W. J., 1980, Preliminary assessment of the risk of volcanism at a proposed nuclear waste repository in the southern Great Basin: U.S. Geological Survey Open-File Report 80-357, 17 p.

Crowe, Bruce, Self, Stephen, Baniman, David, Amos, Robert, and Perry, Frank, 1983, Aspects of potential magmatic disruption of a high-level radioactive waste repository in southern Nevada: Journal of Geology, v. 91, p. 259-276.

Davison, C. C., Keys, W. S., and Paillet, F. L., 1982, Use of borehole-geophysical logs and hydrologic tests to characterize crystalline rock for nuclear-waste storage, Whiteshell nuclear research establishment, Manitoba, and Chalk River nuclear laboratory, Ontario, Canada: Atomic Energy Canada Limited and U.S. Geological Survey, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Technical Report, ONWI-418, UC-70, 103 p.

Fenneman, N. M., 1928, Physiographic divisions of the United States (3rd ed.): Association of American Geographers, Annals, v. 18, no. 4, p. 264-353, map.

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

Gates, J. S., and Kruer, S. A., 1981, Hydrologic reconnaissance of the southern Great Salt Lake Desert and summary of the hydrology of west-central Utah: Utah Department of Natural Resources Technical Publication 71, 55 p.

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

Keys, W. S., and Sullivan, J. K., 1979, Role of borehole geophysics in defining the physical characteristics of the Raft River geothermal reservoir, Idaho: Geophysics, v. 44, no. 6, p. 1116-1141.

Leopold, L. B., 1951, Pleistocene climate in New Mexico: American Journal of Science, v. 249, no. 2, p. 152-168.

Luedke, R. G., and Smith, R. L., 1978a, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-A, scale 1:1,000,000, 2 sheets.

——1978b, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Colorado, Utah, and southwestern Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-B, scale 1:1,000,000.

——1981, Map showing distribution, composition, and age of late Cenozoic volcanic centers in California, and Nevada: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-C, scale 1:1,000,000.

——1982, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Oregon, and Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-1091-D, scale 1:1,000,000.

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

Muffler, L. J. P., ed., 1979, Assessment of geothermal resources of the United States—1978: U.S. Geological Survey Circular 790, 163 p.

Nakata, J. K., Wentworth, C. M., and Machette, M. N., 1982, Quaternary fault map of the Basin and Range and Rio Grande rift provinces, western United States: U.S. Geological Survey Open-File Report 82-579, scale 1:2,500,000, 2 sheets.

Peirce, H. W., 1981, Major Arizona salt deposits: Arizona Bureau of Geology and Mineral Technology, Fieldnotes, v. 11, no. 4, p. 1-4.

Price, Don, and Eakin, T. E., 1974, Water in the Great Basin region, Idaho, Nevada, Utah, and Wyoming: U.S. Geological Survey Hydrological Investigations Atlas HA-487, scale 1:2,000,000.

Roseboom, E. H., Jr., 1983, Disposal of high-level nuclear waste above the water table in arid regions: U.S. Geological Survey Circular 903, 21 p.

Sass, J. H., Diment, W. H., Lachenbruch, A. H., Marshall, B. V., Monroe, R. J., Moses, T. H., Jr., and Urban, T. C., 1976, A new heat-flow contour map of the conterminous United States: U.S. Geological Survey Open-File Report 76-756, 24 p.

Seeburger, D. A., and Zoback, M. D., 1982, The distribution of natural fractures and joints at depth in crystalline rock: Journal of Geophysical Research, v. 87, no. B7, p. 5517-5534.

Simpson, H. E., Weir, J. W., Jr., and Woodward, L. A., 1979, Inventory of clay-rich bedrock and metamorphic derivations in eastern Nevada, excluding the Nevada Test Site: U.S. Geological Survey Open-File Report 79-760, 147 p.

Smith, G. I., Barczak, V. J., Moulton, G. F., and Liddicoat, J. C., 1983, Core KM-3, a surface-to-bedrock record of Late Cenozoic sedimentation in Searles Valley, California: U.S. Geological Survey Professional Paper 1256, 24 p.

Snow, D. T., 1968a, Hydraulic character of fractured metamorphic rocks of the Front Range and implications to the Rocky Mountain Arsenal well: Golden, Colorado, Colorado School of Mines Quarterly, v. 63, no. 1, p. 167-199.

——— 1968b, Rock fracture spacings, openings, and porosities: Journal of Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, v. 94, no. SM1, p. 73-91.

Snyder, C. T., and Langbein, W. B., 1962, Pleistocene lake in Spring Valley, Nevada, and its climatic implications: Journal of Geophysical Research, v. 67, no. 6, p. 2385-2394.

Stauber, D. A., 1983, Crustal structure of north central Nevada from seismic refraction, gravity and surface wave data, in The role of heat in the development of energy and mineral resources in the northern Basin and Range Province: Program with Abstracts, Geothermal Resources Council, May 1983, Reno, Nevada, p. 26.

Thordarson, William, 1965, Perched ground water in zeolitizedbedded tuff, Rainier area and vicinity, Nevada Test Site, Nevada: U.S. Geological Survey TEI-862, 90 p.

Trask, N. J., 1982, Performance assessments for radioactive waste repositories—The rate of movement of faults: U.S. Geological Survey Open-File Report 82-972, 11 p.

U.S. Department of Commerce, 1968, Weather atlas of the United States: Detroit, Michigan, Gale Research Company, 262 p.

——— 1982, Evaporation atlas for the contiguous 48 United States: National Oceanic and Atmospheric Administration, Technical Report NWS 33, 26 p.

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

——— 1981, Radioactive waste disposal in thick unsaturated zones: Science, v. 212, no. 4502, p. 1457-1464.

Winograd, I. J., and Doty, G. C., 1980, Paleohydrology of the southern Great Basin, with special reference to water table fluctuations beneath the Nevada Test Site during the Late(?) Pleistocene: U.S. Geological Survey Open-File Report 80-569, 91 p.

Winograd, I. J., and Thordarson, William, 1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712-C, 126 p.

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