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HYDROLOGY OF YUCCA MOUNTAIN AND VICINITY, NEVADA-CALIFORNIA-- INVESTIGATIVE RESULTS THROUGH MID-1983

HYDROLOGY DOCUMENT NUMBER 12

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 84-4267

Prepared in cooperation with the

U.S. DEPARTMENT OF ENERGY

FRONT COVER: View to southeast across Yucca Mountain, with drill site USW H-3 to lower left

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By R. K. Waddell, J. H. Robison, and R. K. Blankennagel

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Denver, Colorado
1984

UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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CONVERSION TABLE

Multiply metric unit	by	To obtain inch-pound unit
millimeter (mm)	0.03937	inch
millimeter per year (mm/yr)	.03937	inch per year
meter (m)	3.281	foot
kilometer (km)	.6214	mile
liter (L)	.2642	gallon
liter per second (L/s)	1.585×10^{1}	gallon per minute
centimeter (cm)	.3937	inch
degree Celsius (°C)	1.8°C + 32	degree Fahrenheit
meter per second (m/s)	3.281	foot per second
meter per day (m/d)	3.281	foot per day
meter per year (m/yr)	3.281	foot per year
meter squared per day (m^2/d)	10.76	foot squared per day
milligram per liter (mg/L)	1.0	part per million
microgram per liter (μg/L)	1.0	part per billion
microsiemen per centimeter (μS/cm)	1.0	micromho per centimeter
square kilometer (km^2)	.386	square mile
cubic meter (m^3)	35.3	cubic foot
1000 cubic meters (m^3)	.81	acre-foot
meter cubed per second (m^3/s)	35.3	cubic foot per second
cubic meter per second per square kilometer [$(m^3/s)/km^2$]	91.4	cubic foot per second per square mile
meter squared per day (m^2/d)	10.8	foot squared per day
centimeter per second (cm/s)	2835	foot per day
meter cubed per year per square meter [$(m^3/yr)/m^2$]	3.281	foot squared per year per square foot
cubic centimeter per second per square centimeter [$(cm^3/s)/cm^2$]	.3937	cubic inch per second per square inch
milliwatt per square meter (mW/m^2)	.0239	heat-flow unit (HFU)

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ABSTRACT

Yucca Mountain, Nevada, is one of several sites under consideration for construction of the first repository for high-level nuclear waste. This site is underlain by at least 1,800 meters of volcanic tuffs of Tertiary age that are offset by westward-dipping normal faults. Sedimentary rocks of Precambrian and Paleozoic age, primarily limestones and dolomites with some quartzites and slightly metamorphosed shales, stratigraphically underlie volcanic rocks in much of the area.

The climate is arid; no perennial streams are present in the region except those fed by springs, or by snowmelt in the higher mountain ranges. In these few instances, channels contain water for only short distances. No perennial streams exist in the immediate vicinity of Yucca Mountain. Flash floods occasionally occur; debris-flow deposits are known along Fortymile Wash and tributary washes that dissect Yucca Mountain.

Yucca Mountain is located within the Alkali Flat-Furnace Creek Ranch ground-water subbasin, which is tributary to the Death Valley ground-water basin. Under present climatic conditions, most ground-water recharge occurs at Pahute Mesa, at mountain ranges farther north, and perhaps at Timber Mountain. Smaller amounts of recharge probably occur beneath larger washes, such as Fortymile Canyon-Fortymile Wash. Two major ground-water discharge areas occur within the subbasin: (1) Alkali Flat (Franklin Lake), where discharge occurs almost entirely by evapotranspiration; and (2) Furnace Creek Ranch area in Death Valley, where discharge results from numerous small springs.

Beneath Yucca Mountain, depth to ground water ranges from about 460 to about 700 meters. Perched water may be present, but the data are equivocal. Few data are available on the occurrence and movement of water in the unsaturated zone. Recharge at Yucca Mountain is probably less than 5 millimeters per year, and perhaps much less. Within the saturated zone, water moves generally southeast or south, primarily through fractures. The hydraulic gradient is very low on the eastern (downgradient) side of Yucca Mountain. The gradient increases west and north; the increase in gradient is evidence of an area of low permeability. Data on locations of permeable fractures in drill holes are not sufficient for definition of hydrostratigraphic units. However, observations of fracture frequency, as related to lithology, and data obtained from similar rocks beneath Pahute Mesa support the hypothesis that densely welded tuffs fracture more readily than nonwelded and bedded tuffs do; therefore, these tuffs are likely to be more permeable. Proximity

to faults, stress state, and the healing of fractures by mineral deposition affect fracture permeability of a mass of rock and complicate the conceptual model of water movement beneath Yucca Mountain.

Data are not sufficient to predict accurately rates of water movement and travel times. Effective-porosity data are virtually nonexistent. Carbon-14 data provide estimates of velocity in the saturated zone on the order of 3 to 7 meters per year; however, these estimates may be incorrect, because of mixing waters of different ages, uncertainty of locations of recharge areas under wetter climates, and nonconservative transport of bicarbonate ions. Until more water-velocity and effective-porosity data are available, traveltime estimates will be uncertain.

INTRODUCTION

In 1978, the first test hole was drilled at Yucca Mountain as part of a program to determine if suitable rocks exist for construction of a geologic repository for disposal of high-level nuclear waste. Part of Yucca Mountain (fig. 1) is located on the Nevada Test Site and is controlled by the U.S. Department of Energy; the western part of the mountain presently is controlled by the U.S. Bureau of Land Management and the U.S. Air Force. As part of the Nevada Nuclear Waste Storage Investigations, the Department of Energy has supported a test-drilling program and investigations by the U.S. Geological Survey (Interagency Agreement DE-A108-78ET44802), and the Los Alamos, Sandia, and Lawrence Livermore National Laboratories.

Since the first test hole was drilled, many other holes have been completed, so knowledge of the subsurface geology and hydrology has increased substantially. However, because of the amount of time required to support an active drilling program, analysis and publication of much of these data have been delayed. The Nuclear Regulatory Commission requested that the U.S. Department of Energy submit a Site Characterization Report (SCR) (now called Site Characterization Plan) for sites that would be characterized to insure that sufficient data would be collected to enable the Nuclear Regulatory Commission to make decisions on applcations to construct and operate nuclear-waste repositories.

Purpose and Scope

The U.S. Geological Survey participated in the preparation of early drafts of the SCR for the Nevada Nuclear Waste Storage Investigations. Two reports were prepared from the U.S. Geological Survey contributions to the SCR to summarize the geology and hydrology of the Yucca Mountain area. This report discusses hydrology; the other report (U.S. Geological Survey, 1984) discusses the geology. These reports include data collected and analyzed through mid-1983. For this report, the SCR contribution was modified to improve readability and reduce redundancy; otherwise this report closely follows the Standard Content and Format Guide published by the Nuclear Regulatory Commission. The term "Candidate Area" is prescribed by the Nuclear Regulatory Commission; the term refers to the area contained within a 100-km radius of Yucca Mountain. This term has been retained in this adaptation of the SCR.

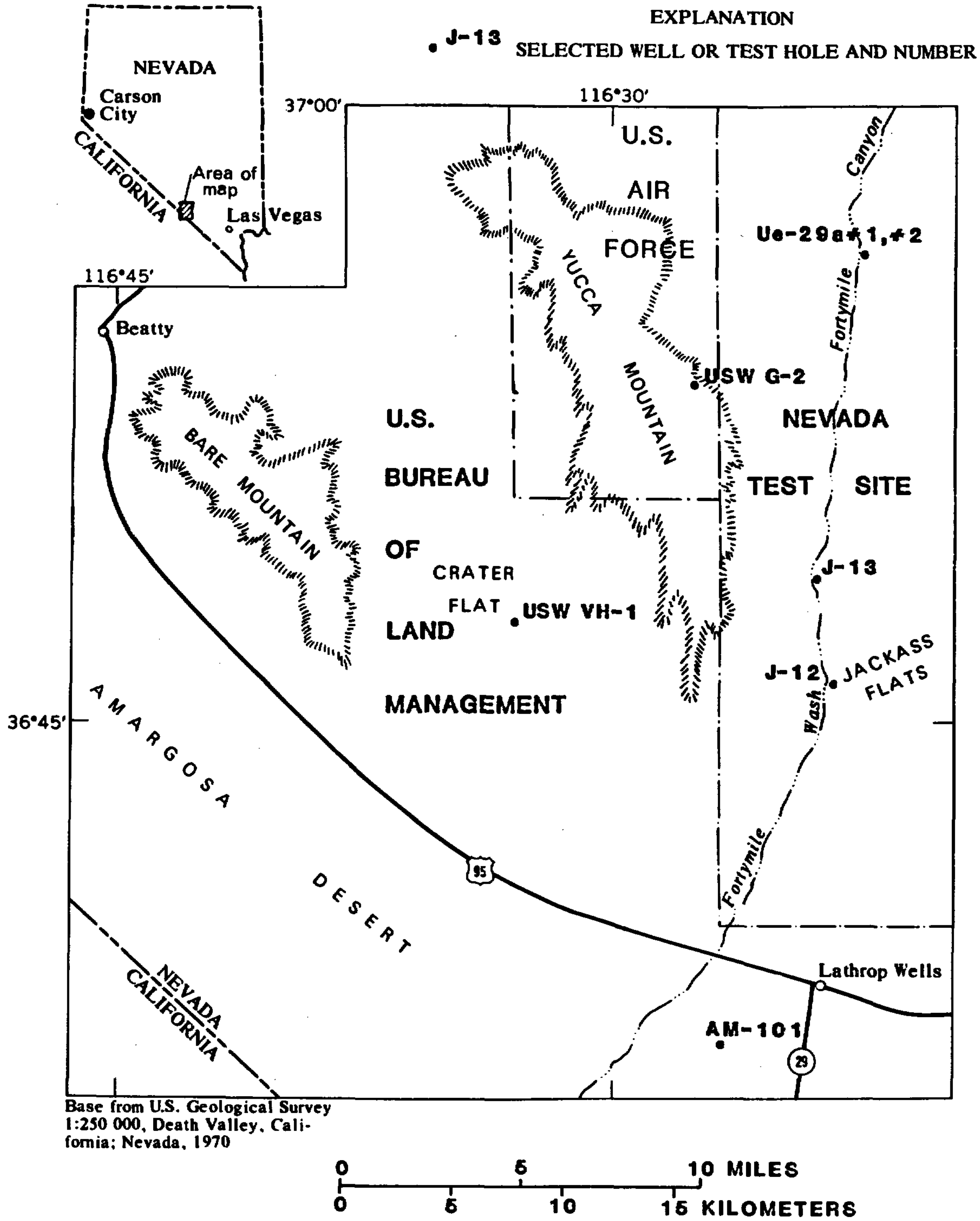


Figure 1.--Location of Yucca Mountain and vicinity.

During the first few years of the studies of Yucca Mountain, the emphasis was on characterizing rocks within the saturated zone. As additional data became available, coupled with the urging of members of the scientific community not directly involved in the Yucca Mountain studies, consideration was given to the unsaturated zone. The unsaturated zone was considered to have several possible advantages over the saturated zone for a repository at Yucca Mountain, including longer travel times, inclusion of a zeolitic tuff with high sorptive properties along the flow path, and avoidance of the potential operational difficulties of a repository beneath the saturated zone. Recently, investigative emphasis has shifted to the unsaturated zone. However, because these studies had not progressed very far by 1983, the unsaturated zone is discussed herein only in a cursory manner.

Physiographic and Geologic Setting

For a more complete description of the physiography and geology of the region surrounding Yucca Mountain, the reader is referred to the companion report (U.S. Geological Survey, 1984) and to the survey of the geology of Nevada by Stewart (1980). The following summary provides an introduction for further reading.

Yucca Mountain is located in southern Nevada (fig. 1), within the Great Basin physiographic province and in the most arid region of the United States. Precipitation ranges from 43 mm/yr in Death Valley to 760 mm/yr in the Spring Mountains (Winograd and Thordarson, 1975, fig. 3). Precipitation is greater at higher altitudes than at lower altitudes. Average annual precipitation at Yucca Mountain is estimated to be 100 to 150 mm. No perennial streams occur in the area; intense thunderstorms cause short-lived flash floods. In the winter, snowfall occurs throughout much of the area, but the snow melts or evaporates quickly except in the higher ranges. The altitude of Yucca Mountain (about 1,460 m) generally is too low for snow to persist for more than a few days.

Geologically, the area is within the Basin and Range Province. Rocks range in age from Precambrian through Holocene. During part of Precambrian and early Cambrian time, this area was part of a rift zone, and quartzites and shales were deposited. During the Cambrian Period, the tectonic setting changed, as rifting occurred progressively farther to the west. The Cordilleran miogeosyncline formed along the western edge of the craton. More than 7,000 m of rocks, principally dolomites and limestones, formed during the remainder of the Paleozoic Era. The area of greatest downwarping and sedimentation occurred east of the Nevada Test Site. To the west, Paleozoic rocks thin and are progressively more siliceous, composed of shales and volcanic debris presumably shed from a volcanic arc farther west.

Although the dominant tectonic mode was underthrusting from west to east, overthrusting also occurred and temporarily created a highland, whose erosion resulted in deposition of shales within an area otherwise dominated by carbonate rocks. Within the Nevada Test Site area, this shale (Eleana Formation) subsequently has undergone minor metamorphism to an argillite. Closure of the Cordilleran miogeosyncline occurred during late Paleozoic or early Mesozoic time, accompanied by folding and overthrusting.

Mesozoic sedimentary rocks are not common in the region, but Mesozoic-age plutons are present in the northeastern part of the Nevada Test Site. Thin sandstones occur in the Spring Mountains near Las Vegas.

During the Tertiary Period, the region became tectonically active again, and Basin-and-Range faulting began. A right-lateral shear zone developed along the Las Vegas Valley, apparently separating active extensional movement to the north from less active movement to the south. A large volcanic field developed in the western part of the Nevada Test Site. At least seven caldera complexes formed, as well as several other smaller eruptive centers, covering the area with rhyolitic lava flows, and ash-flow, airfall, and bedded tuffs. Rocks beneath Yucca Mountain were formed at this time; rocks in the upper 1,000 m were erupted from Crater Flat, Claim Canyon, and Timber Mountain calderas. Yucca Mountain is on the eastern margin of the inferred Crater Flat caldera.

Basin-and-Range faulting continued for a short time after the tuffs composing Yucca Mountain formed. At Yucca Mountain, most faults are normal and dip toward the west. Most rocks dip to the east at 7-11°, although some dip more steeply locally. The part of Yucca Mountain under investigation has a long ridge trending approximately north-south, and is bounded on the west side by a normal fault dipping to the west, forming a steep scarp.

Formation of the Basin-and-Range topography was accompanied by erosion of the ranges, so that alluvial-fan and stream deposits fill the valleys. Thickness of these deposits is highly variable, but this thickness is known to exceed several hundreds of meters in and near the Nevada Test Site.

Because of the arid climate, depth to the water table at places is hundreds of meters. A few small perched springs or seeps occur in the region. Principal ground-water discharge areas occur where rocks of low permeability form barriers to ground-water flow; these major discharge areas are at Ash Meadows, Alkali Flat (Franklin Lake), Death Valley, and Oasis Valley.

SURFACE-WATER HYDROLOGY

Stream Characteristics

The Candidate Area includes most of the Death Valley Basin Hydrographic Region of California-Nevada and a small part of the Central Hydrographic Region of Nevada (which includes parts of California) (pl. 1). The Death Valley Basin in Nevada is characterized by valleys that drain into Death Valley in California via the Amargosa River and its tributaries; whereas, the Central Hydrographic Region is characterized in the Candidate Area by smaller closed basins that contain playas. These hydrographic regions are divided into smaller units called hydrographic areas. The Yucca Mountain site lies on the boundary between Crater Flat and the Fortymile Canyon-Jackass Flats hydrographic areas.

Because of generally arid conditions, no perennial streams occur in the Candidate Area. Perennial surface water comes only from springs, and it is restricted primarily to some short stretches of the Amargosa River, to source pools at some large springs, and to some marshes around the edge of the salt pan in Death Valley (Hunt and others, 1966). One small reservoir, (designated 211 on pl. 1) with a surface area of about 0.28 km^2 and a storage capacity of 300,000 m^3 (Scott and others, 1971, table 6), occurs in the east-central part of the Upper Amargosa hydrographic area (pl. 1). Other features designated as "lakes" on plate 1 are, in fact, playas, that only intermittently contain water.

The Amargosa River originates in Oasis Valley and continues southeastward through the Amargosa Desert past Death Valley Junction, and southward another 75 km, where it turns northwestward, terminating in Death Valley. The river carries floodwaters following cloudbursts or intense storms; the river is normally dry, except for a few short reaches that contain water from springs (Walker and Eakin, 1963), such as the springs that occur in Oasis Valley between Springdale and Beatty (Malmberg and Eakin, 1962), in Ash Meadows northeast of Death Valley Junction, and near Shoshone, about 40 km south of Death Valley Junction. A minimum flow to these segments of the river is maintained by ground-water discharge during the winter, when evapotranspiration is at a minimum. During the summer, discharge from the springs is almost entirely lost by evapotranspiration. During part of the year, ground-water discharges into the river at Alkali Flat, about 7 km south of Death Valley Junction. Data on springs are provided in the later section "Regional ground-water hydrology."

In Death Valley Basin in Nevada, tributaries draining hydrographic areas are all ephemeral. As these streams leave steep mountainous terrain and enter relatively flat valleys, they occupy well-defined incised flood plains, many of which contain meandering low-flow ephemeral streams. During major and infrequent floods, these flood plains may be inundated. The quantity of annual runoff within each of the seven hydrographic areas in the Death Valley Basin in Nye County is estimated at less than 620,000 m^3 (Scott and others, 1971). Because no continuous streamflow stations had been established in the Death Valley Basin Hydrographic Region within or adjacent to the Candidate Area until recently, the frequency and duration of surface-water flow are unknown.

Except for the potential for flooding, surface-water hydrology has little adverse impact on siting a repository at Yucca Mountain, because of the intermittent nature of surface-water runoff and the lack of through-flowing drainages in the Candidate Area. However, washes provide channels for concentrating runoff that may be a principal source of ground-water recharge beneath Yucca Mountain. For example, periodic temperature measurements made in selected wells in Drill Hole Wash during 1981-83 revealed a pronounced change in the character of the temperature profile above a depth of 150 m in drill hole UE-25a#7 in Drill Hole Wash. This change may be related to recharge from a major storm that occurred early in March 1983 (J. H. Sass, U.S. Geological Survey, written commun. 1983).

Flood Potential

Moderate flooding in low-lying areas along major streams in the Candidate Area sometimes has resulted from regional storms that encompassed extensive areas of the Great Basin. However, high-intensity precipitation cells within some regional storm systems often have caused intensive local flooding. Intense flooding is more commonly caused by local convective storms. Thus, although flooding of a serious magnitude can occur over an extensive area, intense floods are generally restricted to relatively small areas and occur as flash floods of short duration.

Flash floods constitute the major flood hazard in the Great Basin. These floods and associated debris flows are probably among the most important geomorphic processes currently active in the Great Basin. They play a major role in development of alluvial fans, denudation of mountainous landscapes, and evolution of drainage-channel morphology. Flood discharges range from water-dominated mixtures to debris flows.

Because streamflow data in the vicinity of Yucca Mountain are sparse, data from a large region were used to estimate flood-flow characteristics near the site, particularly data giving evidence of recent floods in and near drainages having streamflow records. The U.S. Geological Survey has been collecting monthly crest-stage data for many ephemeral washes in the Candidate Area since the early 1960's. Flood records for 12 crest-stage sites are shown on table 1. Locations of four sites closest to Yucca Mountain are shown on plate 1; the remaining sites are outside the Candidate Area and are not shown. Several major floods, occurring on those washes from 1964 through 1980 are given in table 1. The most notable flood was associated with a large winter storm that occurred over the upper Amargosa River drainage basin (drainage area, 1,217 km^2) in February 1969. This storm caused an estimated peak flow of about 450 m^3/s near Beatty (estimated from records for gaging station no. 6, table 1). The upper Amargosa drainage basin is immediately west of Fortymile Wash basin, and the two basins have similar terrains. Also, peak flow of about 97.1 m^3/s occurred in August 1968 at gaging station no. 3 on an unnamed tributary to the Amargosa River near Mercury. This drainage basin has an area of 285 km^2; the basin terrain is similar to Fortymile Wash.

The data indicate that peak flood discharges measured at the 12 gaging stations during the last two decades ranged from approximately 1 $(m^3/s)/km^2$ for drainage areas greater than 100 km^2 to 3 $(m^3/s)/km^2$ for drainage areas less than 5 km^2. This evidence of past severe flooding indicates that occasional severe floods probably will occur in the future within southern Nevada, and may occur at Yucca Mountain.

Yucca Mountain is a long north-south ridge with a maximum altitude of 1,783 m above sea level; most of the ridge crest is at about 1,460 m. The ridge divides the drainage basins of Fortymile Wash to the east and Crater Flat to the west. Crater Flat has no major transecting washes. Fortymile Wash drains from north to south, about 6.5 km east of the Yucca Mountain ridgeline. Where it is adjacent to Yucca Mountain, the streambed decreases in altitude from 1,158 m to 914 m. Flood potential (pl. 2) on Fortymile Wash was evaluated by Squires and Young (1984).

According to Squires and Young (1984, p. 12), "Geomorphic studies have indicated that some of the alluvial surfaces along Fortymile Wash are thousands of years old, which might imply that the surfaces have not been flooded since they were formed several thousand years ago. However, distinct high-water marks were observed along Fortymile Wash in the vicinity of cross-section FM-4..." (pl. 2) indicating that the alluvial surfaces along

Table 1.--*Flood records at selected crest-stage sites in Candidate Area and adjacent areas*

[Squires, Robert R., U.S. Geological Survey, written commun., 1982; Squires and Young, 1984]

Designated number on plate 1	Station name, number and description	Water year 1/	Peak discharge (cubic meters per second) 2/
1	Penoyer Valley Tributary near Tempiute, Nev.	1964	0.00
		1965	.06
		1966	.00
	Station No. 10247860.	1967	.00
		1968	3.68
	Drainage Area = 3.83 km^2.	1969	1.27
		1970	.99
	Period of Record: 1964-80.	1971	.00
		1972	.93
	Lat 37°35'07",long. 115°40' 48", in SE 1/4 NE 1/4 sec. 21,T. 4 S.,R. 56 E., Lincoln County on left bank upstream side of culvert on State Highway 25, one mile northwest of Coyote Summit, and 5.3 miles south of Tempiute.	1973	.00
		1974	.00
		1975	.06
		1976	.02
		1977	.01
		1978	.00
		1979	.01
		1980	.01
2	Indian Springs Valley Tributary near Indian Springs, Nev.	1964	.01
		1965	3.40
		1966	.01
	Station No. 10247890.	1967	.14
		1968	.02
	Drainage Area = 75 km^2.	1969	.71
		1970	.00
	Period of Record: 1964-80.	1971	.34
		1972	14.1
	Lat. 36°34'00", long. 115°48' 40", in NW 1/4 NW 1/4 sec. 16, or SW 1/4 SW 1/4 sec.9, T. 16 S., R. 55 E., Clark County, at culvert on U.S. Highway 95 and 8 miles west of Indian Springs.	1973	.01
		1974	.02
		1975	.06
		1976	.08
		1977	2.83
		1978	.00
		1979	.03
		1980	.02
3	Amargosa River Tributary near Mercury, Nev.	1963	.28
		1964	1.13
		1965	1.05
	Station No. 10251270.	1966	.57
		1967	17.0

Table 1.--*Flood records at selected crest-stage sites in Candidate Area and adjacent areas*--Continued

Designated number on plate 1	Station name, number and description	Water year 1/	Peak discharge (cubic meters per second) 2/
3 (cont.)	Drainage Area = 285 km^2.	1968	97.1
		1969	1.70
	Period of Record: 1963-80.	1970	6.79
		1971	2.55
	Lat. 36°33'40",	1972	43.6
	long. 116°06'00", in sec. 14	1973	5.24
	T. 16 S.,R. 52 E., Nye County, at	1974	.08
	culvert on U.S. Highway 95 and	1975	.02
	9 miles southwest of Mercury.	1976	.00
		1977	.68
		1978	.00
		1979	.68
		1980	.00
4	Amargosa River Tributary	1967	2.68
	No. 1 near Johnnie, Nev.	1968	5.49
		1969	.02
	Station No. 10251271.	1970	9.91
		1971	2.55
	Drainage Area = 5.72 km^2.	1972	.17
		1973	2.77
	Period of Record: 1967-80.	1974	.11
		1975	.28
	Lat. 36°27'36",	1976	.08
	long. 116°06'28", in NE 1/4	1977	2.09
	SE 1/4 sec. 22, T. 17 S.,R. 52 E.,	1978	.31
	Nye County, at culvert State	1979	.00
	Highway 16 and 3.5 miles	1980	.00
	northwest of Johnnie.		
5	Amargosa River Tributary	1968	3.54
	No. 2 near Johnnie, Nev.	1969	.06
		1970	.08
	Station No. 10250272.	1971	.00
		1972	.01
	Drainage Area = 6.45 km^2.	1973	.00
		1974	.00
	Period of Record: 1968-80.	1975	.14
		1976	.06

Table 1.--*Flood records at selected crest-stage sites in Candidate Area and adjacent areas*--Continued

Designated number on plate 1	Station name, number and description	Water year 1/	Peak discharge (cubic meters per second) 2/
5 (cont.)	Lat. 36°26'09",	1977	.08
	long. 116°04'28", in W 1/2	1978	.03
	NE 1/4 sec. 36, T. 17 S.,	1979	.00
	R. 52 E., Nye County, at culvert	1980	.00
	on State Highway 16 and 1.2		
	miles north of Johnnie.		
6	Amargosa River Tributary	1964	.71
	near Beatty, Nev.	1965	.57
		1966	.00
	Station No. 10251220.	1967	119.
		1968	2.55
	Drainage Area = 1,217 km^2.	1969	453.
		1970	.00
	Period of Record: 1964-79.	1971	.00
		1972	.00
	Lat. 36°52'06",	1973	.51
	long, 116°45'34", in NW 1/4	1974	.00
	NE 1/4 sec. 30, T. 12 S.,	1975	11.7
	R. 47 E., Nye County, on left	1976	2.83
	bank, 170 ft. downstream	1977	.05
	from airport road, and 2.8	1978	18.4
	miles south of Beatty.	1979	.00
7	Sarcobatus Flat Tributary, Nev.	1961	.37
		1962	.14
	Station No. 10249050.	1963	.00
		1964	.00
	Drainage Area = 96 km^2.	1965	1.08
		1966	.00
	Period of Record: 1961-80.	1967	.28
		1968	.71
	Lat. 37°13'18",	1969	.82
	long. 117°07'35" in T. 8 S.,	1970	.00
	R. 43 E., Nye County, at culvert	1971	.03
	on State Highway 72, at Bonnie	1972	.00
	Claire, and 24 miles northwest	1973	.17
	of Springdale.	1974	.00
		1975	.42
		1976	.17
		1977	.03
		1978	.02
		1979	.02
		1980	1.78

Table 1.--*Flood records at selected crest-stage sites in Candidate Area and adjacent areas*--Continued

Designated number on plate 1	Station name, number and description	Water year 1/	Peak discharge (cubic meters per second) 2/
8	Palmetto Wash Tributary,	1967	.45
	near Lida, Nev.	1968	.51
		1969	5.46
	Station No. 10249850.	1970	.59
		1971	.70
	Drainage Area = 12.25 km^2.	1972	.01
		1973	.00
	Period of Record: 1967-80.	1974	.00
		1975	.00
	Lat. 37°26'30",	1976	.03
	long. 117°41'25", in SW 1/4	1977	.01
	SE 1/4 sec. 6, T. 6 S.,	1978	.01
	R. 39 E., Esmeralda County,	1979	--
	at culvert on State Highway 3,	1980	.01
	7 miles west of Lida Summit,		
	and 11 miles west of Lida.		
9	Stonewall Flat Tributary, near	1964	.03
	Goldfield, Nev.	1965	.23
		1966	.03
	Station No. 10248970.	1967	1.02
		1968	1.75
	Drainage Area = 1.37 km^2.	1969	4.25
		1970	.00
	Period of Record: 1964-79.	1971	.00
		1972	.03
	Lat. 37°35'40",	1973	.03
	long. 117°12'35", in SE 1/4	1974	.00
	NE 1/4 sec. 13, T. 4 S.,	1975	.00
	R. 42 E., Esmeralda County, at	1976	.03
	culvert on U.S. Highway 95	1977	.01
	and 8 miles south of Goldfield.	1978	.00
		1979	.01
10	Big Smokey Valley Tributary, near	1961	2.55
	Blair Junction, Nev.	1962	.00
		1963	.06
	Station No. 10249680.	1964	.00
		1965	.00
	Drainage Area = 29.5 km^2.	1966	.20
		1967	.03

Table 1.--*Flood records at selected crest-stage sites in Candidate Area and adjacent areas*--Continued

Designated number on plate 1	Station name, number and description	Water year 1/	Peak discharge (cubic meters per second) 2/
10 (cont.)	Period of Record: 1961-79.	1968	.04
		1969	.34
	Lat. 38°01'52",	1970	.00
	long. 117°42'35", Esmeralda	1971	.00
	County, at culvert on U.S.	1972	1.78
	Highway 6 and 95 and 3.5	1973	.40
	miles east of Blair Junction.	1974	.00
		1975	.02
		1976	2.26
		1977	4.81
		1978	.00
		1979	.00
11	San Antonio Wash Tributary, Nev.	1965	.03
		1966	.00
	Station No. 10249135.	1967	.11
		1968	.03
	Drainage Area = 8.86 km^2.	1969	.06
		1970	.62
	Period of Record: 1965-80.	1971	.00
		1972	18.7
	Lat. 38°19'37",	1973	.20
	long. 117°07'25", in SE 1/4	1974	.00
	SW 1/4 sec. 35, T. 6 N.,	1975	.00
	R. 43 E., Nye County, at culvert	1976	.00
	on State Highway 8A and 19 miles	1977	.03
	north of Tonopah.	1978	.00
		1979	.01
		1980	.00
12	Saulsbury Wash, near Tonopah, Nev.	1962	.28
		1963	.00
	Station No. 10249180.	1964	.00
		1965	.00
	Drainage Area = 145 km^2.	1966	1.16
		1967	.28
	Period of Record: 1962-80.	1968	.06
		1969	9.62
	Lat. 38°07'30",	1970	.06
	long. 116°48'30",	1971	.00

Table 1.--*Flood records at selected crest-stage sites in Candidate Area and adjacent areas*--Continued

Designated number on plate 1	Station name, number and description	Water year 1/	Peak discharge (cubic meters per second) 2/
12 (cont.)	SW 1/4 sec. 10, T. 3 N., R. 46 E., Nye County, at culvert on U.S. Highway 6, and 23 miles east of Tonopah.	1972	.76
		1973	.08
		1974	.00
		1975	.00
		1976	2.55
		1978	3.40
		1979	.25
		1980	.00

1/ A water year extends from October 1 through September 30.
2/ Robert Squires (U.S. Geological Survey, written commun., 1982) reported discharge values in cubic feet per second; these have been converted to cubic meters per second and rounded to three significant digits.

Fortymile Wash were inundated. They continue, "From these marks and from data on the cross-sectional area and channel slope, a peak flow of about 20,000 ft^3/s (570 m^3/s) is estimated. Documentation of similar flooding in nearby washes indicates that this flood peak probably occurred during February 1969."

Long-range (thousands of years) flood predictions are difficult to make, even for drainages that have long-term (as much as 100-year) streamflow records. Predictions are especially difficult for drainages with minimal streamflow records, such as those in the Candidate Area. Current flood-prediction methods for this area generally involve some form of statistical evaluation of available regional streamflow data.

Two detailed studies of flood-prone areas in the vicinity of Yucca Mountain provided a basis for estimating the magnitudes of floods with various recurrence intervals. One (Squires and Young, 1984) was an analysis of the flood plain of Fortymile Wash and its southwestern tributaries (pl. 2), in which the magnitudes of the 100- and 500-year flood peaks and "regional maximum" flood were estimated, based on data from extreme floods elsewhere in Nevada and surrounding States. The other study (Christensen and Spahr, 1980) defined flood-prone areas of 100-year, 500-year, and "maximum potential" floods for Topopah Wash and its tributaries in the eastern part of Jackass Flats. The authors of both reports concluded that most floods are caused by convective storms. The "maximum potential" and "regional maximum" floods were estimated by Crippen and Bue (1977, p. 2) from data for historic floods of unusually large magnitude, without reference to recurrence interval, in a five-State region that includes Fortymile Wash: Arizona, California, Nevada, New Mexico, and Utah. These "maximum" flood values, however, do not represent the upper limits of physically possible floods for these drainages.

From their investigation of Topopah Wash, Christensen and Spahr (1980) concluded that:

1. The 100-year flood-prone areas closely parallel most main channels, with few occurrences of out-of-bank flooding of the areas between the main channel and adjacent secondary channels. Out-of-bank flooding would result in a water depth of less than 0.6 m, with a mean velocity as high as 2 m/s occurring on the steeper slopes. Flood-water depth in the stream channels would range from 0.3 to 2.7 m, with mean velocities of 0.9 to 2.7 m/s.

2. The 500-year flood would exceed the discharge capacity of all stream channels except Topopah Wash and some upstream reaches of a few tributaries. Out-of-bank flooding of areas between the adjacent channels would result in water depths as much as 0.9 m, with mean velocities greater than 2 m/s. Flood-water depth in the stream channels would range from 0.3 to 3.7 m, with mean velocities ranging from 0.9 to 4 m/s.

3. The "maximum potential" flood would inundate most of Jackass Flats. Out-of-bank flows in the areas between adjacent channels would have a depth as much as 1.5 m, with a mean velocity as high as 4 m/s. Flood water in the stream channels would have depths of 0.6 to 7 m, with velocities of 1.2 to 7.9 m/s.

Squires and Young (1984) studied the downstream part of Fortymile Wash. Within this area, Fortymile Wash has three tributaries that are informally designated from south to north as Busted Butte Wash, Drill Hole Wash, and Yucca Wash. Approximate flood-prone areas in these washes and areas of potential sheet flow (the overland flow of a thin, continuous film of water) are shown on plate 2. Squires and Young (1984) concluded that:

1. Fortymile Wash, within the flood-study area, is a well-defined, incised channel, with a cross section of 15 to 21 m depth and 300 to 450 m width. The 100-year, 500-year, and "regional maximum" floods would stay within the confines of the wash. Estimated depths of flood water in the stream channel would range from 0.9 to 2.4 m for the 100-year flood, from 1.8 to 3.3 m for the 500-year flood, and from 6.4 to 8.8 m for the regional maximum flood; corresponding mean velocities would be from 1.8 to 2.7 m/s for the 100-year flood, 3.3 to 4.3 m/s for the 500-year flood, and from 7.0 to 8.5 m/s for the regional maximum flood.

2. The drainage basin of Busted Butte Wash varies from a shallow valley with meandering ephemeral streams to a deeply incised canyon in the upstream reaches. Drill Hole Wash is characterized by deep canyons extending from Yucca Mountain to its mid-drainage area. Both washes would have estimated flood-water depths of from 0.3 to 1.2 m in the stream channel during the 100-year flood, and the corresponding mean velocities would range from 1.2 to 2.4 m/s. The 500-year flood would exceed bank capacities at several reaches of the washes. Depths and mean velocities would range from 0.9 to 3.0 m and 1.5 to 3.3 m/s. The "regional maximum" flood would inundate all central flat-fan areas in these two watersheds. Flood-water depths in the stream channels would range from 1.5 to 3.7 m, with mean velocities varying from 2.1 to 4.9 m/s.

3. Yucca Wash is contained within an incised channel that is about 14 m deep and 240 m wide at its confluence with Fortymile Wash. The 100-year, 500-year, and "regional maximum" floods would stay within the steep-side-slope stream banks that contain the flood plain. Flood-water depths in the stream channel would range from 0.9 to 1.5 m for the 100-year flood, from 1.5 to 2.7 m for the 500-year flood, and from 2.7 to 7 m for the regional maximum flood; corresponding mean velocities would vary from 1.5 to 2.7 m/s for the 100-year flood, from 2.4 to 3.7 m/s for the 500-year flood, and from 2.7 to 6.7 m/s for the regional maximum flood.

The extent of erosion and sediment movement caused by flood flow in Forytmile Wash and its tributaries that drain Yucca Mountain is not known quantitatively. Qualitatively, however, erosion of or deposition in channels and flood plains probably would be significant during the 100-year flood, and could be severe during the 500-year and "regional maximum" floods.

Evidence of extensive erosion and deposition was observed in some channels during field surveys. Any significant channel erosion or aggradation in the existing streambeds would alter flood-flow characteristics of cross-sectional area, width, mean velocity, and maximum depth (listed in the report by Squires and Young, 1984). The effect of erosion or deposition on flood-flow characteristics would vary from place to place. Because velocities for the 100- and 500-year and "regional maximum" flood peaks are high, channel erosion and aggradation appear likely.

Although most of Yucca Mountain is well above expected flood levels, areas that are close to channels or within the lower terraces of Fortymile Wash are subject to flooding. Unless adequate precautions are taken, facilities in these areas would be subject to flood damage caused by the movement of both water and debris.

REGIONAL GROUND-WATER HYDROLOGY

Hydrogeologic conditions at the Yucca Mountain site are controlled in part by the broader regional ground-water system. Flow paths and water velocities from the site are determined by rock properties and hydraulic gradients. Because hydraulic gradients are affected by the regional occurrence of permeability, and the locations and amounts of recharge and discharge, knowledge of the regional ground-water system is required for assessment of repository performance, even for a repository in the unsaturated zone.

Hydrogeologic Units

Hydrogeologic units pertinent to the Candidate Area are discussed here briefly. Detailed information regarding these aquifers and aquitards is given in Winograd and Thordarson (1975) and summarized in table 2.

Stratigraphic relationships among hydrogeologic units in and near the Candidate Area are schematically shown in figure 2; geographic relationships are shown in figure 3. In general, structural controls are not reflected in these figures. Extensive faulting and folding of pre-volcanic rocks occurred prior to onset of volcanism, followed by Basin-and-Range style normal faulting and strike-slip faulting associated with Cenozoic tectonism. Accordingly, the general relationships shown in figures 2 and 3 must be interpreted with the understanding that structural controls make the actual situation much more complex; figure 2 does not include any structural features, except faults bounding alluvial basins, which are represented schematically.

Presumably, the lower clastic aquitard underlies the entire area, except where it is intruded by igneous rocks. In figure 3, this unit is shown only where other units are not present in the saturated zone, and the aquitard acts as a barrier to ground-water flow. The upper clastic aquitard, on the other hand, probably occurs only where shown; it also functions as a barrier to flow. Saturated carbonate rocks are present east of a line running approximately from east of Frenchman Flat northward through the Groom Range. Saturated volcanic rocks are present west of a second line that runs from western Jackass Flats northward along the western edge of Yucca Flat. Between these lines, saturated volcanic rocks overlie saturated carbonate rocks; both rocks may contribute to ground-water flow. Where the upper clastic aquitard is shown, saturated carbonate rocks presumably underlie it at great depth (greater than 1,500 m); saturated volcanic rocks may overlie it along its margins. Alluvium locally occurs in the saturated zone. Whether alluvium is saturated depends on the thickness of the alluvium and the depth to the water table. Rocks beneath the saturated alluvium are also saturated. Carbonate rocks probably underlie the saturated alluvium beneath the Amargosa Desert; clastic rocks may also be present.

Table 2.--*Hydrogeologic column for study area*

[m^2/d, square meters per day, cm/s, centimeters per second (Modified from Winograd and Thordarson, 1975)]

SYSTEM	SERIES	STRATIGRAPHIC UNIT	MAJOR LITHOLOGY	MAXIMUM THICKNESS (meters)	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Quaternary and Tertiary	Holocene, Pleistocene and Pliocene		Alluvial fan, fluvial, fanglomerate, lakebed, and mudflow deposits	1,100	Valley-fill aquifer	Transmissivity ranges from 10 to 400 m^2/d; average coefficient of interstitial conductivity ranges from 2.4 x 10^{-4} to 3.3 x 10^{-3} cm/s
Tertiary	Pliocene	Basalt of Kiwi Mesa	Basalt flows, dense and vesicular	75	Lava-flow aquifer	Water movement controlled by primary and secondary fractures and possibly by rubble between flows; intercrystalline porosity and permeability negligible; estimated transmissivity ranges from 5 to 125 m^2/d; saturated only beneath east-central Jackass Flats
		Rhyolite of Shoshone Mountain	Rhyolite flows	600		
		Basalt of Skull Mountain	Basalt flows	75		
	?	Thirsty Canyon Tuff	Ash-flow tuff, partially to densely welded; trachytic lava flows	230	None	Generally unsaturated; present around Black Mountain, northwestern part of study area
	Miocene	Piapi Canyon Group; Timber Mountain Tuff; Ammonia Tanks Member	Ash-flow tuff, moderately to densely welded; thin ash-fall tuff at base	75	Welded tuff aquifer	Water movement controlled by primary and secondary joints in densely welded part of ash-flow tuff; transmissivity ranges from 1 to 1250 m^2/d; intercrystalline porosity and permeability negligible; nonwelded part of ash-flow tuff, where present, has relatively high interstitial porosity (35 to 50 percent) and modest conductivity (10^{-4} cm/s) and may act as a leaky aquitard; saturated only in deeper parts of Yucca, Frenchman, and Jackass Flats
		Piapi Canyon Group; Timber Mountain Tuff; Rainier Mesa Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff near base	175		
		Piapi Canyon Group; Paintbrush Tuff; Tiva Canyon Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff near base	90-100		
		Piapi Canyon Group; Paintbrush Tuff; Topopah Spring Member	Ash-flow tuff, nonwelded to densely welded; thin ash-fall tuff near base	275		

Table 2.--*Hydrogeologic column for study area*--Continued

SYSTEM	SERIES	STRATIGRAPHIC UNIT	MAJOR LITHOLOGY	MAXIMUM THICKNESS (meters)	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Tertiary	Miocene	Piapi Canyon Group — Paintbrush Tuff — Bedded tuff (informal unit)	Ash-fall tuff and fluvially reworked tuff	300	Bedded tuff aquifer	Transmissivity ranges from 2 to 10 m^2/d; saturated only beneath structurally deepest parts of Yucca, Frenchman, and Jackass Flats; occurs locally below ash-flow tuff members of Paintbrush Tuff and below Grouse Canyon Member of Belted Range tuff.
		Wahmonie Formation	Lava-flow and interflow tuff and breccia; locally hydrothermally altered	1200	Lava Flow Aquitard	Water movement controlled by poorly connected fractures; interstitial porosity and permeability negligible; transmissivity estimated less than 5 m^2/d; contains minor perched water in foothills between Frenchman and Jackass Flats
			Ash-fall tuff, tuffaceous sandstone, and tuff breccia all interbedded; matrix commonly clayey or zeolitic	500	Tuff Aquitard	Transmissivity ranges from 1 to 3 m^2/d; interstitial porosity is as high as 40 percent, but interstitial permeability is negligible (3×10^{-7} to 3×10^{-9} cm/s); owing to poor hydraulic connection of fractures, interstitial permeability probably controls regional ground-water movement; perches minor quantities of water beneath foothills flanking valleys; fully saturated only beneath structurally deepest parts of Yucca, Frenchman, and Jackass Flats; Grouse Canyon and Tub Spring Members of Belted Range Tuff may locally be aquifers in northern Yucca Flat.
		Salyer Formation	Breccia flow, lithic breccia, and tuff breccia, all interbedded with ash-fall tuff, sandstone siltstone, claystone, matrix commonly clayey or zeolitic	600		

Table 2.--*Hydrogeologic column for study area*--Continued

SYSTEM	SERIES	STRATIGRAPHIC UNIT		MAJOR LITHOLOGY	MAXIMUM THICKNESS (meters)	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Tertiary	Miocene	(1)				Tuff Aquitard (continued)	
		Belted Range Tuff	Grouse Canyon Member	Ash-flow tuff, densely welded	60		
			Tub Spring Member	Ash-flow tuff, nonwelded to welded	90		
			Local Informal Units	Ash-fall tuff, nonwelded to semiwelded ash-flow tuff, tuffaceous sandstone. Siltstone, and claystone; all massively altered to zeolite or clay minerals; locally minor welded tuff near base; minor rhyolite and basalt	600		
		(1)					
		Rhyolite flows and tuffaceous beds of Calico Hills		Rhyolite, nonwelded and welded ash flow, ash-fall tuff, tuff breccia, tuffaceous sandstone; hydrothermally altered at Calico Hills; matrix of tuff and sandstone commonly clayey or zeolitic	600	Tuff Aquifer/ Aquitard	Rhyolite lavas and ash flows may be transmissive. Bedded tuffs may be zeolitized or argillized and less transmissive. Beneath Yucca Mountain the tuffaceous beds of Calico Hills are mostly within the unsaturated zone
		Crater Flat Tuff	Prow Pass Mountain	Ash-flow tuff, nonwelded to moderately welded, interbedded with ash-fall tuff; matrix commonly clayey or zeolitic	600	Tuff Aquifer/ Aquitard	Transmissivity ranges from less than 0.1 to several hundred m^2/d; ? of fracture characteristics and alteration. Interstitial hydraulic conductivity is small (9×10^{-7} to 4×10^{-4} cm/s).
			Bullfrog Member				
			Tram Member				

Table 2.--*Hydrogeologic column for study area*--Continued

SYSTEM	SERIES	STRATIGRAPHIC UNIT	MAJOR LITHOLOGY	MAXIMUM THICKNESS (meters)	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Tertiary	Miocene	Lithic Ridge Tuff	Ash-flow tuff, partially to densely welded. Commonly argillized	300	Tuff Aquitard	Not well characterized. Transmissivity about 2 x 10^{-4} m^2/d. Interstitial hydraulic conductivity low (3 x 10^{-7} to 7 x 10^{-8} cm/s)
	Miocene (?) Oligocene (?)	Older tuffs and lavas beneath Yucca Mountain	Altered rhyolitic and quartz latitic lavas, and altered bedded and ash-flow tuffs	?		
	Miocene and Oligocene	Rocks of Pavits Spring	Tuffaceous sandstone and siltstone, claystone; fresh-water limestone and conglomerate; minor gypsum; matrix commonly clayey, zeolitic or calcareous	425	Tuff Aquitard	See Salyer Formation above
	Oligocene	Horse Spring Formation	Fresh-water limestone; conglomerate tuff	300		
Cretaceous to Permian		Granitic stocks	Granodiorite and quartz monzonite in stocks, dikes, and sills		(A Minor Aquitard)	Complexly fractured but nearly impermeable
Permian and Pennsylvanian		Tippipah Limestone	Limestone	1100	Upper Carbonate Aquifer	Complexly fractured aquifer; transmissivity estimated in range from 10 to 1250 m^2/d; intercrystalline porosity and permeability negligible; saturated only beneath western one-third of Yucca Flat

Table 2.--*Hydrogeologic column for study area*--Continued

SYSTEM	SERIES	STRATIGRAPHIC UNIT	MAJOR LITHOLOGY	MAXIMUM THICKNESS (meters)	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Mississippian and Devonian		Eleana Formation	Argillite, quartzite, conglomerate, limestone	2400	Upper Clastic Aquitard	Complexly fractured but nearly impermeable; transmissivity estimated less than 5 m^2/d; interstitial permeability negligible but owing to poor hydraulic connection of fractures probably controls ground-water movement; saturated only beneath western Yucca and Jackass Flats; interstitial porosity ranges from 2.0 to 18.3 percent
Devonian	Upper	Devils Gate Limestone	Limestone, dolomite, minor quartzite	425	Lower Carbonate Aquifer	Complexly fractured aquifer which supplies major springs throughout eastern Nevada; transmissivity ranges from 10 to 10,000 m^2/d; intercrystalline porosity 0.4 to 12.4 percent; intercrystalline hydraulic conductivity 1 x 10^{-9} to 5 x 10^{-6} cm/s; solution caverns are present locally but regional ground-water movement is controlled by fracture transmissivity; saturated beneath much of study area
	? Middle	Nevada Formation	Dolomite	460		
Devonian and Silurian		Undifferentiated	Dolomite	430		
Ordovician	Upper	Ely Springs Dolomite	Dolomite	90		
	Middle	Eureka Quartzite	Quartzite, minor limestone	100		
		Pogonip Group: Antelope Valley Limestone	Limestone and Silty Limestone	275		
	? Lower	Pogonip Group: Ninemile Formation	Claystone and limestone interbedded	100		
		Pogonip Group: Goodwith Limestone	Limestone	275		
Cambrian	Upper	Nopah Formation, Smoky Member, Halfpint Member	Dolomite, limestone	325		
			Limestone, dolomite, silty limestone	220		
		Dunderberg Shale Member	Shale, minor limestone	70		

Table 2.--*Hydrogeologic column for study area*--Continued

SYSTEM	SERIES	STRATIGRAPHIC UNIT	MAJOR LITHOLOGY	MAXIMUM THICKNESS (meters)	HYDROGEOLOGIC UNIT	HYDROLOGIC CHARACTERISTICS
Cambrian	Middle	Bonanza King Formation, Banded Mountain Member	Limestone, dolomite, minor Siltstone	750		
		Papoose Lake Member	Limestone, dolomite, minor siltstone	650		
	Lower	Carrara Formation	Siltstone, limestone, interbedded (upper 320 meters predominantly limestone; lower 300 meters predominantly siltstone)	320 290	Lower Carbonate Aquifer (continued)	See preceding page
Precambrian		Zabriskie Quartzite	Quartzite	70	(2) Lower Clastic Aquitard	Complexly fractured but nearly impermeable; supplies no major springs; transmissivity less than 10 m^2/d; interstitial porosity and permeability is negligible but probably controls regional ground-water movement owing to poor hydraulic connection of fractures; saturated beneath most of study area interstitial porosity 0.2 to 10.0 percent; interstitial hydraulic conductivity ranges from 4 x 10^{-11} to 5 x 10^{-9} cm/s.
		Wood Canyon Formation	Quartzite, siltstone, shale minor dolomite	700		
		Stirling Quartzite	Quartzite, siltstone	1025		
		Johnnie Formation	Quartzite, sandstone, siltstone, minor limestone and dolomite	975		

(1) The three Miocene sequences occur in separate parts of the region. Age correlations between them are uncertain. They are placed vertically in table to save space.

(2) The Noonday (?) Dolomite, which underlies the Johnnie Formation is considered part of the lower clastic aquitard.

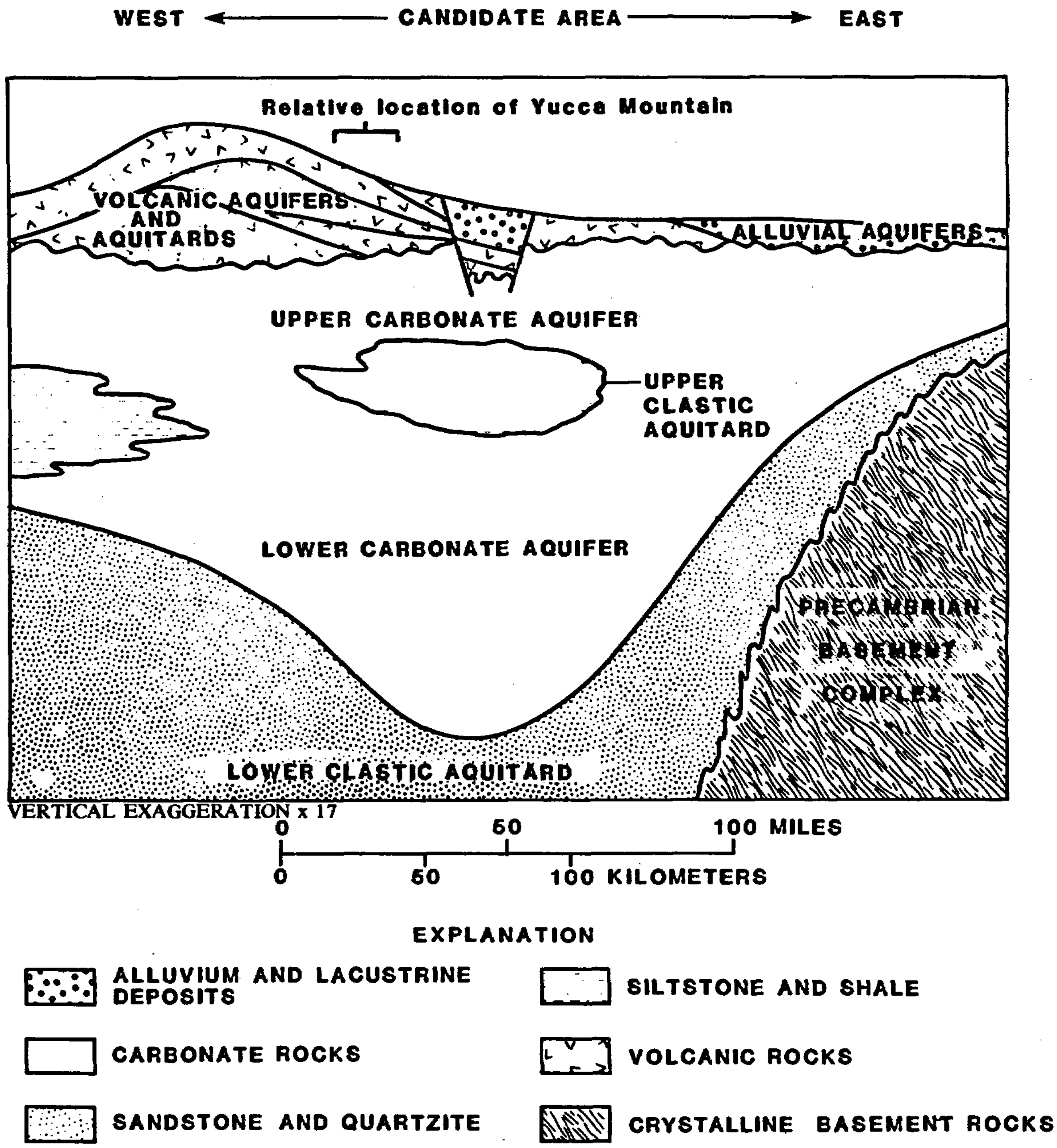


Figure 2.--Stratigraphic relationships among hydrostratigraphic units in the Candidate Area.

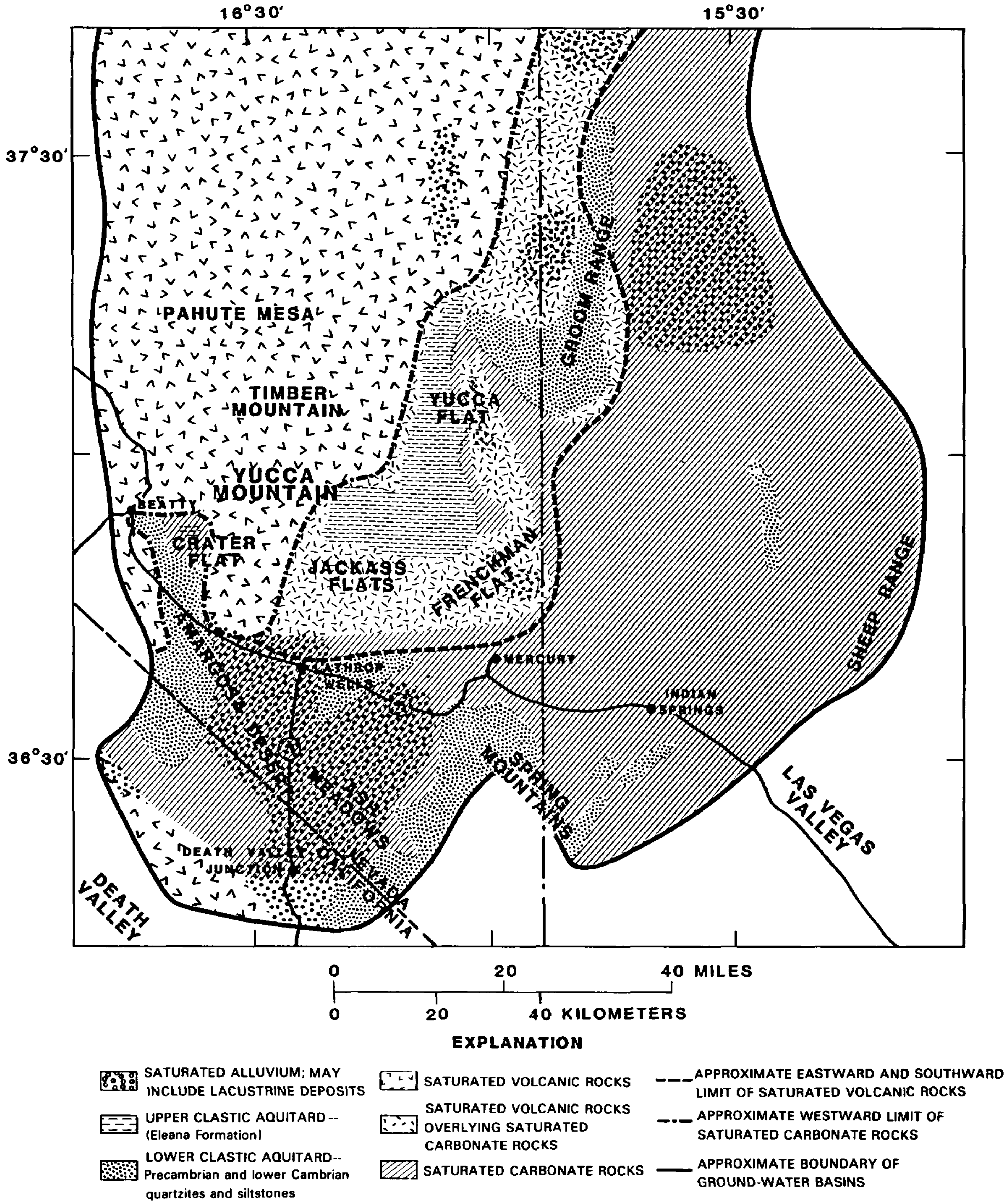


Figure 3.--General geographic distributions of hydrostratigraphic units.

To provide an understanding of the hydrologic framework, regional hydrogeologic units are described briefly in the following paragraphs. Those units that occur within 10 km of Yucca Mountain are the lower clastic aquitard, the lower carbonate aquifer, the volcanic aquitard and aquifer, the lower carbonate aquifer and perhaps the valley-fill (alluvial) aquifer.

Lower Clastic Aquitard

The oldest rocks of hydrologic significance are the upper Proterozoic quartzite and shale of the Johnnie, Stirling, and Wood Canyon Formations, which are approximately 2,700 m thick. With the lower part of the overlying Carrara Formation, these units compose the lower clastic aquitard (Winograd and Thordarson, 1975). Transmissivity of this hydrogeologic unit is approximately 10 m^2/d or less. Because of this small value, the lower clastic aquitard probably significantly affects distribution of hydraulic potentials and locations of ground-water discharge areas.

Lower Carbonate Aquifer

Limestone in the upper part of the Carrara Formation, and the succeeding limestones and dolomites of Cambrian, Ordovician, Silurian, and Devonian age comprise the lower carbonate aquifer. This aquifer is widespread in the eastern part of the Candidate Area, and it is the major water transmitter there. Total thickness of the aquifer exceeds 4,700 m; transmissivities range from 10 to 10,000 m^2/d. High transmissivities probably occur where dissolution has increased fracture aperture or pore diameter. Dissolution is more likely to occur where ground-water flow rates are greater (such as where flow lines are concentrated or where fracture frequency is greater), and where clay content of the carbonate rocks is very low. Therefore, variations in structural setting, proximity to faults, mechanical rock properties, depositional environment, and aquifer thickness probably account for the large variations in transmissivity. Hydraulic gradients generally are small because of high transmissivity.

Upper Clastic Aquitard

The Eleana Formation (Devonian and Mississippian age) constitutes the upper clastic aquitard. The Eleana, which consists primarily of argillite, with minor quartzite and limestone, is approximately 2,400 m thick, with a transmissivity of 5 m^2/d or less.

Upper Carbonate Aquifer

The Tippipah Limestone of Pennsylvanian and Permian age constitutes the upper carbonate aquifer. Although more than 1,000 m thick, it is of minor regional hydrologic significance, because it is saturated only in western Yucca Flat. Where the upper clastic aquitard is absent (eastern part of Candidate Area), this aquifer is not hydrologically separable from the underlying lower carbonate aquifer. Transmissivity of this unit ranges from about 10 to 1,250 m^2/d.

Granite

Small granitic bodies of Mesozoic age occur at the northern end of Yucca Flat. Being small, they locally serve as an aquitard. They are complexly fractured, but nearly impermeable. The flow that does occur is through fractures (Walker, 1962); drifts within the Climax Stock (430 m deep, but above the water table) are nearly dry.

Volcanic Rocks

Volcanic rocks of Tertiary and Quaternary ages, consisting of ash-flow and ash-fall tuffs (nonwelded to welded) and basalt and rhyolite flows, occur in the western and central parts of the Candidate Area. They have variable hydrologic properties; some are aquifers; others are aquitards. Because of their complex stratigraphy, these units are not easily traceable on a regional scale. Aggregate thickness of these volcanic rocks is unknown, but it exceeds several thousand meters.

Rock properties are dependent not only on the eruptive history, but also on the cooling history, post-depositional mineralogic changes, and the structural setting. The permeability of ash-flow tuff is in part a function of the degree of fracturing, and, thus, the degree of welding (Winograd, 1971; Blankennagel and Weir, 1973). Densely welded tuff fractures readily; nonwelded tuff does not. Degree of welding varies with vertical position within a cooling unit and distance from the source (Smith, 1960). Therefore, distribution of permeability is affected by the irregular distribution of tuff lithologies, and it is a function of proximity to the various eruptive centers. Permeability probably is also a function of proximity to faults and fracture zones. Another factor affecting permeability is chemistry of the water as a function of position along a flow line (Claassen and White, 1979). Incongruent dissolution of glass along the flow path results in relative increases in dissolved solids. At some point along the flow path, this water becomes more sodic as montmorillonite and zeolites precipitate. Precipitation of these minerals in fractures decreases permeability. Calcite, and iron manganese oxides are also present in fractures. Transmissivity of these volcanic rocks ranges from about 1 to 1,250 m^2/d.

Beneath Yucca Mountain, volcanic rocks are composed of nonwelded to densely welded ash-flow tuffs, and bedded, reworked, and air-fall tuffs. The proposed repository horizon, the Topopah Spring Member of the Paintbrush Tuff, is a moderately to densely welded tuff, with a few intercalated bedded tuffs. The Topopah Spring Member is above the water table beneath Yucca Mountain, but it is an aquifer beneath Fortymile Wash east of Yucca Mountain. Beneath the Topopah Spring Member are the tuffaceous beds of Calico Hills, the Crater Flat Tuff, the Lithic Ridge Tuff, and older, unnamed tuffs and lava flows.

Few data are available on anisotropy in tuffs. Because of the importance of fractures in contributing to permeability, their frequency, orientation, interconnectivity, and aperture largely determine the directional characteristics of permeability in welded and, perhaps, nonwelded tuffs. Orientation and frequency data are being collected in both outcrop and drillholes, but these studies have not been completed. Preliminary results of these studies indicate that two sets of faults and fractures are present (Scott and others, 1983). The first set strikes north-northwest (N. 15° W. to N. 40° W.), and dips steeply (60° - 90°) to the west. The second strikes north-northeast (N. 5° E. to N. 35° E.), and also dips steeply to the west. The minimum compressive stress is oriented approximately N. 50° W. to N. 60° W. which is coincident with the regional direction of tectonic extension (Carr, 1974). Fractures with these orientations may tend to be closed by tectonic stresses, whereas fractures with orientations of N. 30° E. to N. 40° E. may tend to be more open. Therefore, the north-northeast-striking fracture set may be more transmissive; however, multiple-well pressure tests to test this hypothesis have not been performed yet.

Most fractures are steeply dipping, and vertical permeability within a single cooling unit may be approximately the same as maximum horizontal permeability within a single cooling unit. However, because of nearly horizontal layering in ash-flow tuffs, due to emplacement and cooling mechanics, and because of the presence of bedded, nonwelded tuffs, vertical variations in fracture frequency probably occur. If the volume of rock under consideration contains bedded or nonwelded tuffs, vertical permeability may be of the same order of magnitude or less than maximum horizontal permeability. Vertical permeabilities have not been measured.

Interconnectivity of fractures within the partially to moderately welded Crater Flat Tuff has been demonstrated by pumping tests of intervals penetrated by drill hole UE-25b#1. A 61-m long segment of the hole was pumped for 29 days at a rate of 10.7 to 12.7 L/s, a total withdrawal of approximately 3×10^7 L. At the end of the test, the maximum drawdown was approximately 12 m. Removal of this quantity of water probably affected a large volume of rock, especially when the low storativity of the fractured rock is considered. During the test, a solution of sodium bromide was placed in test hole UE-25a#1, in an interval approximately 100 m horizontally from, and 100 m vertically above, the pumped interval in UE-25b#1. Bromide was detected in the discharge water within 3 days of being placed in UE-25a#1. Therefore, at this location, connectivity of fractures is known to occur over a large volume of rock, in both vertical and horizontal directions.

Valley-Fill Aquifer

Valley fill of Tertiary and Quaternary age is composed of alluvial-fan, fluvial, fanglomerate, lakebed, and mudflow deposits. The character of valley-fill material results from distance from source, relationship to alluvial channels, and type of source material.

Grain size decreases from the proximal to the distal ends of alluvial fans, and away from distributary channels on the fans. Because runoff intensity varies from event to event, interbedding of fine- and coarse-grained material occurs in valley fill. This condition results in vertical hydraulic conductivities much less than horizontal conductivities.

Alluvial-fan, fluvial, and fanglomerate deposits are primarily sand and gravel; therefore, these deposits have higher hydraulic conductivity than lakebed and mudflow deposits, which contain mainly clay-sized material.

These fine-grained deposits have conductivities several orders of magnitude smaller than sand and gravel. Transmissivities for alluvial-fill deposits range from about 10 to 400 m^2/d (Winograd and Thordarson, 1975).

Valley-fill material is generally saturated only beneath the structurally deepest parts of the flats in the Candidate Area, and where present in, and upgradient from, discharge areas. Beneath most of the Amargosa Desert, alluvium is the principal aquifer.

Relationships Among Hydrogeologic Units

Geology of the area is complex; therefore, relationships among the hydrogeologic units are complex also. Based on knowledge of regional geology, sedimentary rocks of Precambrian and (or) Paleozoic age probably underlie the entire area, except where intruded by granitic bodies. Thicknesses of overlying units range from zero to thousands of meters. Volcanic rocks are concentrated in the northwestern half of the Candidate Area (Carr and others, 1984; Jennings, 1977; Stewart and Carlson, 1978); volcanic rocks are absent in many parts of the southeastern half of the area.

Because of complex folding and faulting from the Paleozoic Era to the Quaternary Period, "layer-cake" models of the hydrostratigraphic units are not appropriate. Because of this complexity, relationships among hydrogeologic units are discussed only in a general way. Locations and rates of recharge affect hydrologic relationships. In general, water moves with a downward component near recharge areas, and with an upward component near discharge areas. Discharge areas occur where low-permeability rocks impede flow of water. A high gradient may develop across the aquitards, causing relatively high hydraulic heads upgradient of the barrier. If these heads are high enough to intersect land surface, springs may form.

In a general way, water moves up or down relative to the stratigraphic section if its flow has a vertical component. Beneath Yucca Flat, water moves downward progressively from alluvium through tuffs, and into carbonate rocks. At Ash Meadows, a discharge area southeast of Yucca Mountain, water moves upward from the lower carbonate aquifer into the alluvium; volcanic rocks are not present. However, beneath eastern Pahute Mesa (60 to 80 km north of Yucca Mountain), the thickness of volcanic rocks probably exceeds 3 km; underlying sedimentary rocks, if present, have no observable effect on the ground-water system beneath Pahute Mesa.

Potentiometric Levels

Ground-water potentiometric levels in the Candidate Area, referenced to sea level, are presented on plate 3. Data sources include Eakin (1962, 1963, 1966), Malmberg and Eakin (1962), Walker and Eakin (1963), Malmberg (1967), Rush (1970), Thordarson and Robinson (1971), Winograd and Thordarson (1975), and Miller (1977). Contour lines in the illustration are drawn at 100-m intervals. Composite water levels from several hydrogeologic units were used in mapping the contours. In Yucca Flat, data are available from wells completed in alluvium, tuff, and carbonate rocks. The potentials indicate downward flow into the lower carbonate aquifer (Doty and Thordarson, 1983). However, the potentiometric levels are similar enough that, on a regional scale, contouring data from different geologic units is not feasible.

Steep gradients occur adjacent to areas of high recharge and in areas of low permeability. Gradients are low where high-permeability carbonate rocks and alluvium are present in the saturated zone. A very steep gradient may exist near the northwestern side of Death Valley; however, the only available data points are springs. These springs appear to issue from perched ground water; if so, the actual gradient is much less there than shown.

Ground water flows generally southward or southwestward through most of the Candidate Area; however, flow is westerly in the southeastern part. Available data (pl. 3) indicate that the upgradient boundary of the ground-water basin passes through the Goldfield Hills, the Cactus, Kawich, Reveille, Grant, Golden Gate, Pahranagat, and Sheep Ranges, and the Spring Mountains. The downgradient boundary is Death Valley, the lowermost discharge area.

Areas of Recharge and Discharge

Recharge Areas

The potentiometric surface (pl. 3) and the distribution of precipitation were used to estimate recharge areas. Recharge occurring in the northern tract of the area, where a potentiometric high occurs, is indicated on plate 3.

Maps showing lines of equal precipitation have been used as a reconnaissance tool to estimate recharge in the southern Great Basin. Empirical precipitation-recharge relationships have been developed from mass-balance estimates for many basins in southern Nevada (Eakin and others, 1963; Walker and Eakin, 1963; Rush, 1970). These relationships generally indicate that, as mean annual precipitation increases, the percentage of precipitation that is recharged to the ground-water system also increases. At mean annual precipitation rates of less than 150 to 200 mm/yr, the recharge rate becomes small enough that mass-balance methods are not sensitive. Areas of greater precipitation include the Spring Mountains, and the Sheep, Pahranagat, and Belted Ranges. Mean annual precipitation is less than 150 mm/yr throughout Death Valley, the Amargosa Desert, and Jackass, Crater, Frenchman, and Yucca Flats. Winograd and Friedman (1972) and Winograd and Thordarson (1975) caution that the use of precipitation maps for estimating recharge can lead to large errors, because they ignore factors such as intermittent streamflow, topography, and the nature of surficial materials.

Discharge Areas

Places in the Candidate Area where ground water naturally discharges are characterized by rocks of relatively lower permeability occurring downgradient from the discharge area (Dudley and Larson, 1974; Winograd and Thordarson, 1975; and Waddell, 1982). At these locations, a steep potentiometric gradient occurs across the barrier, and the water table intersects the land surface.

Locations of springs within the Candidate Area are shown on plate 4. Major discharge areas are the Ash Meadows spring lineament, Alkali Flat (Franklin Lake), Furnace Creek Ranch area, and Oasis Valley. Minor discharge from regional aquifers occurs at Indian Springs and Cactus Springs. Numerous perched springs of minor and variable discharge are present throughout the area. Discharge at Alkali Flat is primarily by evapotranspiration rather than spring discharge.

Data on springs within the Alkali Flat-Furnace Creek Ranch ground-water subbasin, including Yucca Mountain, are given in tables 3 and 4. All but two of the springs listed are in California, either in or near Death Valley. The springs emerge from the lower carbonate aquifer, from volcanic rocks, or from alluvium. Springs emerging from volcanic rocks have low discharges and are probably perched. Springs with discharges greater than 0.3-0.6 L/s issue from the lower carbonate aquifer or alluvium overlying it.

Numerous springs (pl. 4) in the southern and western parts of the Candidate Area were identified as sources of water supply in Thordarson and Robinson's (1971) inventory of wells and springs within approximately 160 km of eastern Pahute Mesa. The main concentrations of springs used for water supply are in Death Valley in the vicinity of Furnace Creek Ranch, approximately 50 to 60 km southwest of Yucca Mountain; in Oasis Valley in the vicinity of Beatty, approximately 25 km northwest of Yucca Mountain; and at Ash Meadows, approximately 40 to 60 km south-southeast of Yucca Mountain.

In the Furnace Creek Wash area, which is part of Death Valley National Monument, California, 60 points of ground-water discharge, including artificial diversions, springs, seeps, and phreatophyte areas, were described and mapped by Pistrang and Kunkel (1964). The measured and estimated total discharge from these points is a minimum of 0.16 m^3/s.

At Stovepipe Wells Hotel, northwest of Furnace Creek Ranch, potable water was trucked for many years from a storage tank at Emigrant Ranger Station, 14 km southwest of the hotel and 655 m higher. The storage tank is supplied by a buried pipeline from Emigrant Spring, in Emigrant Canyon, about 8 km south of the ranger station, at an altitude of about 1,158 m (Miller, 1977). Miller estimated that flow from the spring probably averaged 0.19 L/s during the winter, when demand was greatest, and 0.13 L/s during the summer. In 1973, the National Park Service constructed an underground-storage tank in the alluvial fan south of Stovepipe Wells Hotel, and began trucking water to it from Nevares Spring, near the mouth of Furnace Creek Wash.

White (1979) provided information on probable aquifer type, discharge rates, and chemical analyses of water for many of the springs in Oasis Valley. Dudley and Larson (1974) provided similar data for the springs at Ash Meadows.

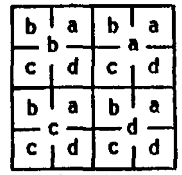
Other springs identified by Thordarson and Robinson (1971) as sources of water for irrigation and for domestic and stock supply are scattered throughout the southern part of the Candidate Area. Most of these are located along the Panamint Range, near the southwestern perimeter of the Candidate Area; in the Spring Mountains area, approximately 60 to 100 km southeast of the site; and in the vicinity of Indian Springs, approximately 75 km southeast of the site.

Table 3.--*Data for selected springs in Death Valley National Monument and vicinity, California and Nevada*[1/].

Location number: Based on location in the rectangular system for subdivision of public land. For example, in the number 17N/6E-5QS1, the part of the number preceding the slash indicates the township (T. 17 N.), the part between the slash and the hyphen is the range (R. 6 E.), the number between the hyphen and letter indicates the section (5). For sites in California, the first capital letter (Q) indicates the quarter-quarter section as shown in the accompanying diagram. For sites in Nevada, the first lower-case letter following the section number designates the quarter section (see accompanying diagram), and the second lower-case letter designates the quarter-quarter section. The letter S refers to spring, and the final number (1) is a serial number assigned to sites within the quarter-quarter section.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

Section (California)



Section (Nevada)

Spring name	Spring number	Flow, in liters per second	Date of measurement	Dissolved solids, in milligrams per liter (approximate)	Specific conductance, in microsiemens (approximate)	Remarks
Sheep Creek	17N/6E-5QS1	0.6	4/25/67	800	1,200	
Saratoga	18N/5E-2ES1,2	4.7	4/27/67	3,100	4,700	Combined flow of two springs from large pool.
Rhodes	21N/4E-11MS1	.007	3/23/70	500-700	750-1,000	Perched spring in southern Black Mountains.
Willow (Gold Valley)	23N/3E-54JS1	.6	4/15/69	800	1,200	Flow varies between 0.1 and 1.2 liters per second.
Eagle Borax	24N/1E-15DS1	19	---	1,600	2,500	---
Tule	25N/1E-33FS1	Very low flow	5/06/67	2,000	3,000	---
Texas	27N/1E-23BS1	13.2	12/08/76	600	1,000	Discharge is from interbasin flow.
Travertine	27N/1E-23,25, 26S	44	1/06/77	600	1,000	Discharge is from interbasin flow; aggregate of several springs.
South Travertine	27N/1E-26BS1	31	1/06/77	640	1,020	Discharge is from interbasin flow; near Nevares Springs
Unnamed	28N/1E-36FS1	2.5	1/07/77	550	850	---
Nevares	28N/1E-36GS1	14	1/07/77	630	1,000	Discharge is from interbasin flow; aggregate of several springs.
Unnamed	7S/40E-15adS1	.01	---	300	500	Upgradient from Roosevelt Well in Magruder Mountain area, Nevada.
Sand	9S/41E-7RS1	.0025	5/01/68	850	1,300	Northern headwaters of Death Valley.
Grapevine	11S/42E-2,3,10S	28	---	650-800	1,000-1,200	Numerous outlets; flow given is aggregate.
Mesquite	11S/42E-27RS1	.57	---	900	1,300	Largest spring in floor of northern Death Valley.
Staininger s	11S/43E-18ES1	12.5	---	480	730	Supplies Scotty's Castle; probably interbasin flow.

Table 3.--*Data for selected springs in Death Valley National Monument and vicinity, California and Nevada*[1/].--Continued

Spring name	Spring number	Flow, in liters per second	Date of Measurement	Dissolved solids, in milligrams per liter (approximate)	Specific conductance, in microsiemens (approximate)	Remarks
Surprise	11S/43E-18S1,2	.3	---	480	700	Supplies Grapevine Ranger Station; perched water in volcanic rocks.
Brier	11S/44E-32bcS1	.06	---	200	320	---
Quartz	13S/41E-26MS1	.001	2/14/67	480	800	Important to bighorn-sheep habitat.
Klare	13S/45E-4LS1	.1	11/17/68	570	880	---
Goldbelt	15S/42E-32CS2	.02	5/20/71	150-200	250-400	---
Keane Wonder	15S/46E-1RS1	1.9	11/17/68	3,100	4,500	---
Jackass	16S/42E-18RS1	.2	4/23/68	---	---	---
Cottonwood	16S/42E-25KS1	4.6	4/24/68	350	520	---
Tucki	16S/45E-29DS1	.6	6/10/57	---	---	---
Emigrant	17S/44E-27BS1	.12	11/09/71	350	550	---
Upper Emigrant	17S/44E-27KS1	.05	11/09/71	530	850	---
Wildrose	19S/44E-21RS1	.5	1/05/72	500	800	Supplies ranger station.
Greater View	23S/45E-23QS1	.02	4/27/67	350	520	At Russell Camp.
Willow (Butte Valley)	23S/46E-30CS1	.4	4/28/67	320	500	---
Squaw	23S/46E-33DS1	1.3	5/15/67	350	540	---

1/ Adapted from Miller, 1977.

Table 4.--*Records of selected springs in parts of Inyo County, California and Nye County, Nevada*[1].

Location number: Based on location in the rectangular system for subdivision of public land; locations with townships south use the Mount Diablo Base Line, and locations with townships north use the San Bernadino Base Line. In the number 22N/07E-30E1, the part of the number preceding the slash indicates the township (T. 22 N.), the part between the slash and the hyphen is the range (R. 7 E.), the number between the hyphen and letter indicates the section (30), the letter (E) indicates the quarter-quarter section as shown in the accompanying diagram (California only), and the final number (1) is a serial number assigned to sites within the quarter-quarter section. All listed springs are in California except the last two, which are in Nevada.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

Section (California)

Discharge: Some springs are intermittent; some are perennial.

Location name	Location number	Altitude, in meters	Water-bearing rock	Discharge rate, in liters per second	How determined	Date (month and year)	Water use	Temperature, in degrees Celsius
Unnamed	22N/3E	634	-------	--------	----------	---------	-------------	---------
Shoshone	22N/7E-30E1	494	-------	28	Estimated	---------	Public supply	33
Unnamed	22N/1E-01	-76	-------	--------	----------	---------	-------------	---------
Willow	22N/3E	817	-------	--------	----------	---------	-------------	---------
Greenwater	23N/3E	1,548	-------	--------	----------	---------	-------------	---------
Eagle Borax	20S/1E	-79	Valley fill	--------	----------	---------	-------------	---------
Unnamed	20S/2E	-79	do.	--------	----------	---------	-------------	25
Unnamed	29N/1E-35N1	-86	do.	0.3	Estimated	3-57	Unused	26
Tule	19S/1E	-79	do.	0.3	do.	---------	-------------	16
Lemonade	25N/2E	1,548	Volcanic rock	--------	----------	---------	-------------	---------
Navel	26N/2E-13	634	Valley fill	--------	----------	---------	-------------	---------
Unnamed	27N/1E-30B	-79	do.	--------	----------	---------	-------------	---------
Travertine	27N/1E	122	do.	139	Estimated	---------	-------------	32
Do.	27N/1E-25D1	122	do.	6	----------	1-57	-------------	33
Unnamed	27N/1E-26A7	98	do.	--------	----------	---------	Irrigation	36
Unnamed	27N/1E-26A6	98	do.	--------	----------	---------	do.	34
Travertine	27N/1E-26A5	98	do.	17	Estimated	11-56	do.	29
Do.	27N/1E-26A4	98	do.	0.3	do.	12-56	do.	34

Table 4.--*Records of selected springs in parts of Inyo County, California and Nye County, Nevada*[1/].--Continued

Location name	Location number	Altitude, in meters	Water-bearing rock	Discharge rate, in liters per second	How determined	Date (month and year)	Water use	Temperature, in degrees Celsius
Do.	27N/1E-26A3	98	do.	0.3	do.	do.	-------------	32
Do.	27N1E-26A2	98	do.	14	do.	do.	Irrigation	33
Unnamed	27N/1E-26B5	98	do.	0.01	do.	---------	Unused	---------
Unnamed	27N/1E-26B4	98	do.	0.01	do.	---------	do.	---------
Unnamed	27N/1E-24N1	122	do.	0.01	do.	---------	-------------	---------
Travertine	27N/1E-23R1	122	do.	19	----------	1-57	-------------	33
Unnamed	27N/1E-23Q1	98	do.	0.01	Estimated	---------	Unused	---------
Unnamed	27N/1E-23Q6	98	do.	0.01	do.	---------	do.	---------
Unnamed	27N/1E-23Q5	98	do.	0.01	do.	---------	do.	---------
Unnamed	27N/1E-23Q4	98	do.	0.01	do.	---------	do.	---------
Unnamed	27N/1E-23Q3	98	do.	0.3	do.	12-57	do.	22
Unnamed	27N/1E-23Q2	98	do.	0.01	do.	---------	do.	---------
Unnamed	27N/1E-23K2	122	do.	0.3	do.	---------	do.	---------
Unnamed	27N/1E-23K1	125	do.	0.01	do.	---------	do.	---------
Unnamed	27N/1E-23L3	49	do.	0.01	do.	---------	do.	---------
Unnamed	27N/1E-23L1	49	do.	0.01	do.	---------	do	---------
Unnamed	27N/1E-23F1	49	do.	0.3	do.	2-57	do.	27
DV Hotel Tunnel	27N/1E-22H1	15	Valley fill	9	Estimated	3-57	----------	33
Texas	27N/1E-23B1	116	do.	14	do.	1-57	Domestic	33
Unnamed	17S/47E-18C	79	do.	--------	----------	---------	----------	---------
Unnamed	27N/1E-09	-73	do.	--------	----------	---------	----------	---------
Unnamed	27N/1E-03P1	-3	do.	0.3	Estimated	12-57	Unused	23
Unnamed	17S/46E-12	-79	do.	--------	---------	---------	---------	---------
Unnamed	27N/1E-03K1	30	do.	0.03	Estimated	---------	Unused	---------

Table 4.--*Records of selected springs in parts of Inyo County, California and Nye County, Nevada*[1/].--Continued

Location name	Location number	Altitude, in meters	Water-bearing rock	Discharge rate, in liters per second	How determined	Date (month and year)	Water use	Temperature, in degrees Celsius
Unnamed	27N/1E-04B	-73	do.	--------	----------	---------	----------	---------
Cow	27N/1E-03A1	61	do.	1	Estimated	3-57	Unused	38
Unnamed	28N/1E-34N1	3	do.	0.06	do.	12-56	do.	23
Nevares	28N/1E-36K1	280	do.	0.01	----------	do.	----------	21
Do.	28N/1E-36M2	227	do.	--------	----------	---------	----------	29
Do.	28N/1E-36M1	219	do.	2	----------	12-56	----------	26
Unnamed	28N/1E-35K1	158	do.	0.01	Estimated	3-58	Unused	24
Salt	17S/46E	-73	do.	0.1	do.	---------	----------	31
Nevares	28N/1E-36G2	273	do.	1	---------	12-56	----------	39
Do.	28N/1E-36G1	286	do.	17	---------	do.	----------	40
Do.	28N/1E-36	280	do.	3	Estimated	---------	----------	39
Do.	28N/1E-36G1	280	do.	22	do.	12-55	Domestic	39
Warm	-----------	-79	do.	0.1	do.	---------	-----------	32
Unnamed	28N/1E-32A	-79	do.	-------	----------	---------	-----------	--------
Unnamed	16S/46E-33	-79	do	-------	----------	---------	-----------	--------
Salt	28N/1E-21N	-79	do.	0.06	Estimated	---------	Unused	16
Unnamed	----------	-79	do.	0.3	do.	---------	-----------	16
Unnamed	28N/1E-01	363	do.	-------	----------	---------	-----------	--------
Unnamed	29N/2E-30	631	---------	-------	----------	---------	-----------	--------
Specie	12S/48E-30	1,366	Sedimentary rock	-------	----------	---------	-----------	--------
Topopah	----------	1,768	Volcanic rock	0.01	----------	3-58	Unused	12

1/ Modified from Thordarson and Robinson (1971).

Principal Ground-Water Flow Paths

In general, ground-water movement is from the recharge areas to the discharge areas discussed previously. If the rocks are isotropic with respect to transmissivity, movement would be perpendicular to equipotential lines and toward areas of lower hydraulic potential. However, because equipotential lines shown on plate 3 are based on unevenly distributed data, and because it is unlikely that these rocks are isotropic, flow directions probably are not perpendicular to equipotential lines. Data are not sufficient to determine the amount of anisotropy, so no attempt has been made to determine actual flow direction; equipotential lines may be used only to approximate the general direction of flow.

The Candidate Area includes parts of three ground-water subbasins: Oasis Valley, Ash Meadows, and Alkali Flat-Furnace Creek Ranch (pl. 3). A subbasin consists of recharge areas and flow paths to a major discharge area. The Ash Meadows and Oasis Valley subbasins are actually sub-subbasins within the Alkali Flat-Furnace Creek Ranch subbasin; the Alkali Flat-Furnace Creek Ranch subbasin is part of the Death Valley ground-water basin.

Because the rocks that cause springs to form have low but non-zero hydraulic conductivities, small amounts of ground-water flow through them as underflow. At Oasis Valley, water also flows through alluvium over the underground "spillway" created by the lower clastic aquitard, but the water remains in the ground-water system. At Ash Meadows, water probably flows through alluvium into the Alkali Flat-Furnace Creek Ranch subbasin; many of the springs emerge from alluvium. In both areas, water discharged from the springs, if not used for irrigation, flows only a short distance on the surface until it either evaporates, is transpired by plants, or seeps back into the ground-water system. The amount that reenters ground water is probably small, because of the large water demand of plants in a desert environment. The amount of ground water moving from the Oasis Valley and Ash Meadows subbasins to the Alkali Flat-Furnace Creek Ranch subbasin is unknown, because of uncertainties in the hydraulic conductivities and thicknesses of the ground-water dams, the amount of evapotranspiration, and the amount of flow over the spillways through alluvium. These contributions of water to the Alkali Flat-Furnace Creek Ranch subbasin probably are small.

The Alkali Flat-Furnace Creek Ranch subbasin, in turn, is tributary to discharge in Death Valley. Rocks of the lower clastic aquitard crop out at Eagle Mountain just south of Alkali Flat. Both leakage of water through this barrier, and movement through alluvium in the Amargosa River channel, probably occur.

Oasis Valley Subbasin

Discharge at Oasis Valley is caused by the presence of low-permeability rocks downgradient from Beatty; this discharge has been estimated to be 0.078 m^3/s (Malmberg and Eakin, 1962). Water flows into Oasis Valley from western and central Pahute Mesa. Although the boundary between the Oasis Valley subbasin and the northern part of the Alkali Flat-Furnace Creek Ranch subbasin is not well-known, it probably extends approximately from Beatty to the northeast along Beatty Wash and into eastern Pahute Mesa. The subbasin is small, extending only about 70 km north-south and about 20 km east-west.

The Oasis Valley subbasin contains volcanic rocks, unconsolidated alluvial and perhaps lacustrine deposits, Proterozoic and Paleozoic clastic and carbonate rocks, and deep-seated granitic rocks. Volcanic rocks dominate the subbasin. Paleozoic and Proterozoic rocks crop out only locally in the Bullfrog Hills just west of Oasis Valley, and at the southwestern edge of the basin at Beatty; these units probably do not greatly affect the flow of ground water. Alluvium is locally important as an aquifer in Gold Flat. Granitic rock was penetrated in a drill hole in central Pahute Mesa (J. W. Hasler and F. M. Byers, Jr., U.S. Geological Survey, written commun., 1965) and it may underlie Black Mountain. These granitic rocks may provide a lower boundary for the flow system, or may be small barriers to ground-water flow, depending on their extent.

Alkali Flat-Furnace Creek Ranch Subbasin

The northern boundary of this subbasin, which includes Yucca Mountain, is along a line that crosses the Cactus, Kawich, and Reveille Ranges (pl. 3). The eastern boundary is well-established in the northern part, where it lies along a line running through the axes of the Reveille and Belted Ranges. Southward, this boundary is more obscure. Water flows eastward across a barrier (composed of the upper clastic aquitard) along the west side of northern Yucca Flat; however, whether this water discharges at Ash Meadows or flows beneath Rock Valley and eastern Jackass Flats is not known. The boundary with the Ash Meadows basin is better-known near Ash Meadows, extending from the Skeleton Hills northeastward to the northern end of the Specter Range. From there, its location is uncertain. Because of low hydraulic conductivity of the upper clastic aquitard, little water flows across it.

A geologic section that extends from Pahute Mesa to Alkali Flat and Eagle Mountain is included on plate 3. This section shows that the northern part of the subbasin is underlain by volcanic rocks associated with several calderas. Both Basin-and-Range-style faults and faults associated with caldera formation are present. Granitic rocks probably underlie most of the caldera areas (Byers and others, 1976), but the hydraulic gradient across Timber Mountain caldera is low (pl. 3). This low gradient may be caused by high-permeability volcanic rocks (in which case granitic rocks must be too deep to affect the "shallow" ground-water system), and (or) caused by recharge occurring near Timber Mountain.

The southern part of the subbasin is underlain mostly by unconsolidated deposits. From approximately 10 km north of Amargosa Valley (formerly Lathrop Wells) southward past Alkali Flat, alluvium is within the saturated zone. Aeromagnetic data (Greenhaus and Zablocki, 1982) show that volcanic rocks are scarce beneath the Amargosa Desert. Presumably Paleozoic or Precambrian rocks underlie the alluvium, but details of their lithology and structure are unknown. In a 467-m deep hole (AM-101, fig. 1) in alluvium near Amargosa Valley, depth to water is approximately 73 m; thus, saturated alluvium is at least 394 m thick. Downgradient, depth to water progressively decreases, until it is only a few meters below land surface at Death Valley Junction. Beneath the Franklin Lake playa, an upward gradient exists, and the hydraulic head is above land surface. Certainly flow occurs in the alluvium, but the influence of the Paleozoic and Precambrian rocks beneath the alluvium is unknown.

Carbonate rocks of Paleozoic age occur in the southern part of the Funeral Mountains across the Amargosa Desert from Yucca Mountain. Springs near Furnace Creek Ranch at the eastern edge of Death Valley discharge water from these carbonate rocks, either directly or indirectly through overlying alluvium. Some of these springs are several hundred meters above the floor of Death Valley. Lakebeds or impermeable zones along Furnace Creek fault system may form barriers, causing the water to discharge some distance up the slope, rather than at the base.

The origin of water discharged in the Furnace Creek Ranch area is uncertain, but its chemistry strongly resembles that of water in the alluvium in the central Amargosa Desert (Winograd and Thordarson, 1975). Water discharging at Furnace Creek Ranch is probably a mixture of water from all three subbasins.

Discharge by evapotranspiration at Alkali Flat was estimated to be 0.39 m^3/s (Walker and Eakin, 1963). Flow across the barrier at Eagle Mountain was estimated to be about 0.02 m^3/s; discharge near Furnace Creek Ranch was estimated to be about 0.20 m^3/s (Hunt and others, 1966). Total flux (volumetric flow rate) in the Alkali Flat-Furnace Creek Ranch subbasin, not including the discharge in the Oasis Valley and Ash Meadows subbasins, is estimated to be about 0.61 m^3/s, or 53,000 m^3/d.

Ash Meadows Subbasin

The Ash Meadows subbasin adjoins the Alkali Flat-Furnace Creek Ranch subbasin on the east. The northern boundary runs from Reveille Range eastward to Grant Range. The eastern boundary is along the axes of Golden Gate, Pahranagat, and Sheep Ranges. Spring Mountains form the southern boundary. All boundaries associated with ranges are ground-water divides, and are a result of greater amounts of precipitation associated with higher elevations. Between Pahranagat and Sheep Ranges, ground water probably flows from Pahranagat Valley into Desert Valley (Eakin, 1966; Winograd and Thordarson, 1975). Winograd and Friedman (1972) estimated that 35 percent of the discharge at Ash Meadows is derived from Pahranagat Valley.

A favorable hydraulic gradient for flow between Pahrump Valley and Ash Meadows may exist; however, the unnamed hills between them are underlain by rocks of the lower clastic aquitard. Therefore, the amount of flow, if any, from Pahrump Valley to Ash Meadows probably is very small.

Flow in the subbasin is primarily in Paleozoic limestone and dolomite. Potential gradients are low, because of high transmissivities of soluble carbonate rocks. Distribution of head and direction of flow are greatly affected by the presence of low-permeability rocks (Winograd and Thordarson, 1968, 1975). An example is the steep gradient across the Las Vegas Valley shear zone (pl. 3), where Indian Springs and Cactus Springs occur. Movement along the shear zone resulted in either juxtaposition of low-permeability rocks, or, more likely, development of low-permeability fault gouge (Winograd and Thordarson, 1968, 1975).

Another example of the effect of low-permeability rocks is the steep gradient across Groom Range, where the lower clastic aquitard is present. Here, water flowing from western Emigrant Valley to eastern Emigrant Valley is impeded by quartzites of Precambrian and Cambrian ages in the Groom-Papoose Range fault blocks. The same low-permeability rocks also retard flow from western Emigrant Valley southward into Yucca Flat.

A schematic section (Winograd and Thordarson, 1975, pl. 1) from the Eleana Range to Ash Meadows shows ground water flowing downward through alluvium and volcanic rocks into underlying carbonate rocks beneath Yucca Flat. The potentiometric level is lower in carbonate rocks than the overlying rocks (Winograd and Thordarson, 1975; Doty and Thordarson, 1983). Potentiometric levels in carbonate rocks affect the potentiometric level in overlying rocks; because carbonate rocks transmit most of the water, their permeabilities must be greater than those of the overlying rocks.

Carbonate rocks transmit most of the water in the subbasin, but other lithologies are locally important. Northeast of the Ash Meadows spring line, the saturated thickness of alluvium probably is more than 100 m. Beneath Yucca and Frenchman Flats, both alluvium and volcanic rocks are saturated. However, most of the alluvium beneath Yucca Flat is unsaturated. Springs at Indian Springs discharge from alluvium, though carbonate bedrock crops out nearby.

Discharge in Ash Meadows is estimated to be 0.66 m^3/s (Walker and Eakin, 1963; Dudley and Larson, 1976). A normal fault, downthrown to the southwest (Healey and Miller, 1971), probably juxtaposes low-permeability lakebed deposits on the downthrown side against rocks of the lower carbonate aquifer, forcing flow upward (Dudley and Larson, 1974). Discharge is from springs in alluvial sediments downgradient (southwest) of the fault. The northern and southern ends of the spring line are probably determined by the presence of the lower clastic aquitard in the subsurface 10 to 15 km southwest of the Skeleton Hills (northern end), and by the northern end of the Resting Springs Range (southern end). These low-permeability rocks form boundaries parallel to flow for the Ash Meadows subbasin between Ash Meadows and the Specter Range; therefore, almost all the discharge at Ash Meadows must pass through a relatively narrow zone beneath the Specter Range. Regional transmissivities of about 40,000 m^2/d have been calculated (Winograd and Thordarson, 1975) for the lower carbonate aquifer in this area; this figure is six to nine times greater than that determined from aquifer tests (Leap, D. I., Purdue University, written commun., 1979).

Isotopic and Regional Hydrochemistry

Major-ion chemistry of ground water in the vicinity of Yucca Mountain was summarized by Winograd and Thordarson (1975), White (1979), Claassen (1983), and Benson and others (1983). Water chemistry is determined by interactions between water and reactive components of rock and soil zones through which the water has traveled. These interactions include dissolution and precipitation reactions.

A map of hydrochemical zones portraying major-ion composition is presented in Winograd and Thordarson (1975). Chemistry of water is, in part, indicative of the types of rocks with which the water has been in contact; therefore, this chemistry may be useful as an indicator of flow paths. However, because of the complex geology and differences in climatic regime during the past 20,000 to 40,000 years, water chemistry does not provide an unambiguous clue to flow path.

Chemistry of ground water within the Candidate Area is principally determined by: (1) Reactions with carbonate and volcanic rocks or rock fragments; (2) concentration of dissolved chemicals by evaporation; (3) precipitation of smectites, zeolites, and evaporative minerals; and (4) mixing of waters of different chemistry. Reactions with shales, quartzites, or granitic rocks do not produce significant changes in water chemistry within the study area. Water throughout the Candidate Area is generally potable, except where evapotranspiration results in waters with high dissolved-solids content, such as beneath Alkali Flat, southeast of Death Valley Junction. In a few mineralized areas, ground-water quality is poor enough that alternate supplies are being used.

Chemical data on water from wells and springs in the region around and downgradient of Yucca Mountain are provided in tables 5, 6, and 7. Additional data are presented by Winograd and Thordarson (1975), who included data from most of the Candidate Area, and by Claassen (1983), who studied ground-water chemistry in the Amargosa Desert.

In the eastern part of the flow system (principally the Ash Meadows subbasin), the most common rocks are limestones and dolomites; thus, the principal ions are calcium, magnesium, and bicarbonate (Winograd and Thordarson, 1975; Winograd and Pearson, 1976). Sodium is commonly a major constituent also, indicating possible contact with volcanic rocks. The pH of these waters ranges from approximately 7.4 to 7.8. The waters contain 2 to 5 mg/L dissolved oxygen. Temperatures range from 26 to 64 $^{\circ}$C; the highest reported temperature, from Test Well F southeast of Skull Mountain, is anomalous and it is probably due to local hydrothermal activity. Most reported temperatures are less than 35 $^{\circ}$C. Little is known about dissolved organic-carbon compounds; measurements of total organic-carbon concentrations of three water samples from springs in Ash Meadows ranged from 1.0 to 2.2 mg/L.

Chemistry of waters from tuffaceous rocks is derived principally by dissolution of rhyolitic volcanic glass and subsequent precipitation of various zeolites and smectite clays (Claassen and White, 1979, and White, 1979). Dominant ions are sodium (50 to 150 mg/L) and bicarbonate (100 to 300 mg/L); calcium is present in lesser amounts (5 to 20 mg/L) and magnesium in amounts less than 5 mg/L. These waters also contain dissolved oxygen at concentrations of 2 to 5 mg/L. The pH ranges from about 7 to 8.

Chemistry of water in alluvium is determined by the type of detrital material and rocks with which the water has been in contact. Therefore, water in alluvium, where tuffaceous detritus is the dominant reactive material has a chemistry similar to water in tuffs. Water in playa or lacustrine deposits, such as beneath parts of the Amargosa Desert, has a dissolved-solids concentration of 600 to 900 mg/L, as compared with 200 to 400 mg/L for

Table 5.--*Chemical analyses of spring water in the Furnace Creek Wash area of California*[1/].

Location number: Based on location in the rectangular system for subdivision of public land. For example, in the number 27N/1E-3A1, the part of the number preceding the slash indicates the township (T. 27 N.), the part between the slash and the hyphen is the range (R. 1 E.), the number between the hyphen and letter indicates the section (3), the letter (A) indicates the quarter-quarter section as shown in the accompanying diagram, and the final number (1) is a serial number assigned to sites within the quarter-quarter section.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

Section

Water-bearing zone: Qyal, younger alluvium; Qoal, older alluvium; Qt, travertine; Qf, fanglomerate; QTℓ, lacustrine deposits.

Method of collection: F, natural flow; P, pumped.

Source of analytical data: DPH, California Department of Health: DWR, California Department of Water Resources; GS, U.S. Geological Survey.

Location name	Location number	Water-bearing zone	Interval sampled (meters below land surface)	Method of collection	Date of collection	Temperature (degrees Celsius)	pH (units)	Dissolved chemical constituents, in milligrams per liter: Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Silica (SiO_2)	Hardness as $CaCO_3$	Dissolved solids (evaporation)	Specific conductance (microsiemens per centimeter)	Source of analytical data
Cow Spring	27N/1E-3A1	Qf	Surface	F	4-8-55	38	8.3	45	20	146	10	345	0	178	37	2	1.9	.61	--	195	603	702	DWR
Salt Springs	27N/1E-3K1	QTℓ	do.	F	12-1-56	--	---	--	--	---	--	---	--	---	180	3.6	--	11	--	46	---	2,360	GS
Salt Springs	27N/1E-3P1	do.	do.	F	12-1-56	23	---	--	--	---	--	---	--	--	22,200	11	--	327	--	214	---	56,800	Do.
Tunnel at Furnace Creek Inn	27N/1E-22H1	Qyal	do.	F	4-5-57	33	7.6	40	22	180	13	378	0	208	50	2.5	0	1.6	26	190	810	1,140	DWR
Texas Spring Tunnel	27N/1E-23B1	QTℓ	do.	F	11-27-53	--	8.5	36	21	160	11	310	17	166	54	4	0	1	--	176	634	1,000	Do.
Texas Spring Tunnel		do.	do.	F	4-11-56	31	7.8	35	18	154	12	342	--	156	35	3.7	1.9	.88	--	162	607	953	Do.
Texas Spring Tunnel		do.	do.	F	4-5-57	33	7.9	35	20	155	12	348	0	160	43	2	0	1	25	170	716	1,010	Do.
Travertine Springs	27N/1E-23R1	do.	do.	F	4-22-54	32	8.1	38	20	150	14	354	0	165	40	4	1	.86	--	177	593	966	Do.
Travertine Springs	27N/1E-25D1,2	do.	do.	F	4-11-56	31	7.7	36	19	159	12	351	0	169	37	4	3.7	.88	--	168	616	968	Do.
Travertine Springs	27N/1E-25D1	do.	do.	F	3-25-54	32	8.0	26	22	145	11	321	--	158	39	3	0	0	43	155	---	949	GS

Table 5.--*Chemical analyses of spring water in the Furnace Creek Wash area of California*[1/].--Continued

Location name	Location number	Water-bearing zone	Interval sampled (meters below land surface)	Method of collection	Date of collection	Temperature (degrees Celsius)	pH (units)	Dissolved chemical constituents, in milligrams per liter: Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Silica (SiO_2)	Hardness as $CaCO_3$	Dissolved solids (evaporation)	Specific conductance (microsiemens per centimeter)	Source of analytical data
Sump in Furnace Creek Wash	27N/1E-26B1	Qyal	do.	F	4-11-56	27	7.5	40	20	160	12	363	0	179	41	4	2.9	1.5	--	182	644	1,020	DWR
Undeveloped spring	28N/1E-34N1	QTℓ	do.	F	12-1-56	23	7.7	52	38	253	16	455	0	352	74	4.4	---	1.3	--	284	---	1,580	GS
Nevares Spring	28N/1E-36G1	Qt	do.	F	11-30-53	--	8.2	38	32	250	15	403	10	307	77	4	0	1.1	--	227	938	1,420	DWR
Nevares Spring		do.	do.	F	11-29-56	40	7.9	42	22	138	12	317	0	173	34	2.9	1.8	1.2	--	192	625	-----	DPH
Nevares Spring	28N/1E-36K1	do.	do.	F	3-3-57	21	7.7	30	43	403	30	575	0	535	101	2	---	1.7	--	250	---	2,120	GS
Test well Furnace Creek Wash	27N/1E-24E	Qoal	30-73	P	11-24-58	36	8.1	32	23	140	11	322	0	157	40	1	---	1	--	176	---	955	GS

1/ Modified from Pistrang and Kunkel (1964).

Table 6.--*Chemical analyses of ground water and surface water along Amargosa River drainage, Nevada and California*[1/].

Location number: Based on location in the rectangular system for subdivision of public land. For example, in the number 16S/48E-36b, the part of the number preceding the slash indicates the township (T. 16 S.), the part between the slash and the hyphen is the range (R. 48 E.), the number between the hyphen and letter indicates the section (36), and the letter (b) indicates the quarter section as shown in the accompanying diagram that shows the Nevada system for subdividing sections.

b	a
c	d

Section

Method of collection: F, flowing.

Source of analytical data: GS, U.S. Geological Survey

Location name or number	Interval sampled (meters below land surface)	Method of collection	Temperature (degrees Celsius)	pH (units)	Dissolved chemical constituents, in milligrams per liter: Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Silica (SiO_2)	Hardness as $CaCO_3$	Dissolved solids (evaporation)	Specific conductance (microsiemens per centimeter)	Source of analytical data
Lathrop Wells (now Amargosa Valley) Well	? - 171	--	--	8.2	14	1.5	106	4.4	160	0	103	20	2	6.3	---	48	41	382	568	GS
Well 16S/48E-36b	? - 50	--	23	7.9	70	3.9	62	9	142	0	107	61	1.4	17	---	82	190	489	700	Do.
Franklin Well near Death Valley Junction	------	--	13	8.0	64	54	1,020	68	1,690	0	530	150	8	1.1	1.2	125	382	3,070	4,740	Do.
Ash Meadow Ranch Spring	Surface	F	--	8.1	16	4.4	55	8.8	161	0	36	7.5	2	4.1	---	88	58	299	372	Do.
Ash Meadow Big Spring	do.	F	28	7.7	45	18	98	8.8	314	0	110	25	1.4	.3	.51	32	186	468	780	Do.
Carson Slough 18S/50E-5d	do.	F	10	8.5	40	26	125	16	362	10	122	40	2	0	.68	28	207	566	937	Do.
Death Valley Junction Well	------	--	21	8.7	2	1	330	11	546	28	154	49	6.4	0	1.5	34	9	854	1,410	Do.
Death Valley Junction Highway Department	------	--	--	8.9	2	.5	374	12	594	41	180	53	7.2	0	1.1	24	7	965	1,560	Do.
Amargosa River 24N/6E-18b	Surface	F	4	8.8	24	29	344	40	542	33	277	123	2.8	0	2.1	26	179	1,140	1,860	Do.

1/ Modified from Hunt and others (1966).

Table 7.--*Chemical analyses of water in Death Valley National Monument and vicinity, California*[1/].

Location number: Based on location in the rectangular system for subdivision of public land. For example, in the number 26N/2E-5Q1, the part of the number preceding the slash indicates the township (T. 26 N.), the part between the slash and the hyphen is the range (R. 2 E.), the number between the hyphen and letter indicates the section (5), the letter (Q) indicates the quarter-quarter section as shown in the accompanying diagram, and the final number (1) is a serial number assigned to sites within the quarter-quarter section. Where the analyzed water is from a spring rather than a well, an S is inserted before the final digit. Where a Z is substituted for the quarter-section designation, the location is from an unverified description.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R

Section

Water-bearing zone: Br, crystalline bedrock; Fd, fanglomerate deposits; Qtℓ, lacustrine deposits; Se, edge of saltpan; Sp, saltpan; Tv, Tertiary volcanic rock.

Method of collection: F, flowing.

Source of analytical data: DA, U.S. Department of Agriculture; DWR, California Department of Water Resources; GS, U. S. Geological Survey.

Location name	Location number	Water-bearing zone	Interval sampled (meters below land surface)	Method of collection	Date of collection	Temperature (degrees Celsius)	pH (units)	Dissolved chemical constituents in milligrams per liter														Specific conductance (microsiemens per centimeter)	Source of analytical data
								Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Silica (SiO_2)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Dissolved solids (evaporation)		
Borate Mine	26N/2E-5Q1	Qtℓ	?-15	-	1-7-72	14	8.0	350	87	990	7.5	460	2,900	220	1.1	.6	590	12	1,200	860	5,390	5,830	GS
Lemonade Spring	25N/2E-13GS1	Tv	Surface	F	11-18-68	12	7.1	2.2	2.1	180	7.4	260	79	64	.8	13	1.3	57	14	---	533	797	Do.
Navel Spring	26N/2E-13FS1	Fd	Surface	F	5-16-74	23	8.2	30	11	160	8.4	300	100	76	2	31	3.2	18	120	---	590	1,030	Do.
Test Well	25N/1E-33F2	Se	?-16	-	3-22-70	21	7.4	75	40	250	7	130	250	400	.3	0	1.3	21	350	250	1,100	1,840	Do.
Test Well	25N/1E-33H1	Sp	?-16	-	3-12-70	28	8.1	14	13	2,400	470	790	470	3,600	5.4	0	---	--	---	---	----	12,100	DWR
Badwater Spring	24N/2E-4BS1	Se	Surface	F	1-30-59	12	7.5	830	95	8,050	330	110	2,800	11,400	9.8	0	344	26	2,500	2,400	23,600	35,000	GS
Eagle Borax Spring	24N/1E-15DS1	Se	Surface	F	11-?-54	--	7.1	610	270	760	28	320	1,400	1,800	1.2	.7	4.4	42	2,600	----	5,130	7,730	Do.
Test Well	24N/1E-15E1	Se	?-15	-	5-17-74	28	7.9	63	35	110	7.5	110	170	200	.4	.2	.58	28	500	210	673	1,190	Do.

Table 7.--*Chemical analyses of water in Death Valley National Monument and vicinity, California*[1/].--Continued

Location name	Location number	Water-bearing zone	Interval sampled (meters below land surface)	Method of collection	Date of collection	Temperature (degrees Celsius)	pH (units)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Silica (SiO_2)	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Dissolved solids (evaporation)	Specific conductance (microsiemens per centimeter)	Source of analytical data
								Dissolved chemical constituents in milligrams per liter															
Test Well	24N/1E-27D1	Se	?-10	-	4-27-68	30	7.5	48	78	74	4	130	180	43	.8	0	.68	--	190	---	495	692	DWR
Test Well	23N/1E-35Z1	Se	?-3	-	4-22-32	15	7.6	430	320	2,050	92	320	610	4,400	---	.6	6.7	37	---	---	8,160	14,000	DA
Hidden Spring	22 1/2N /3E-19QS1	Tv	Surface	F	4-7-67	13	7.8	5.7	1.2	50	5	110	21	15	.6	.6	.3	59	19	---	212	265	GS
Willow Spring	22 1/2N /3E-18JS1	Br	Surface	F	1-12-66	20	7.8	60	14	67	5	360	88	57	.5	1	.78	--	210	---	365	729	DWR

1/ Modified from Miller (1977).

tuff-derived water, and 200 to 300 mg/L for carbonate-derived water. Water from playas where discharge occurs has a highly variable composition (Winograd and Thordarson, 1975, p. C99).

Mixing of waters from carbonate and tuffaceous sources is indicated by the chemistry of waters in parts of Ash Meadows and Alkali Flat-Furnace Creek Ranch ground-water subbasins, especially beneath the southern Amargosa Desert and near Furnace Creek Ranch. Chemistry of the water beneath Yucca Mountain probably is derived solely by reaction with tuffaceous rocks.

Carbon-14, oxygen, and hydrogen isotopic data for the Candidate Area are presented on plate 5. Carbon-14 ages have not been corrected for dissolution of old or "dead" carbon. Interpretation of the carbon-14 data is complicated by possible mixing of waters of different ages and different origins, because of differences in depths of water-yielding intervals in wells. Where water is sampled from volcanic rocks, and where samples show no evidence of dissolution of calcite, the ages probably approximate true ages. However, caliche is present along Fortymile Wash, and calcite occurs along fractures beneath Yucca Mountain; therefore, a minor correction may be appropriate. Problems resulting from mixing require that data be examined carefully, with an understanding of the influences of present and past hydrologic conditions, in order to make meaningful interpretations.

The large areal variability of carbon-14 ages of waters southwest of Amargosa Valley strongly indicates that the hydrologic model appropriate for modern climatic conditions (in which most recharge occurs in areas of higher altitude) probably is not entirely appropriate for climatic conditions during the Pleistocene Epoch. From a detailed study of chemistries of waters in this area, Claassen (1983) concluded that, during a period approximately 9,000 to 17,000 years ago, runoff from melting snow was sufficient to allow recharge to occur beneath drainage channels in the Amargosa Desert. The subsequent period, and perhaps the preceding one as well, were too dry for widespread recharge to occur. Carbon-14 ages of 4,100, 3,800, and 2,280 years (Waddell, 1984) for samples taken from test holes UE-29a#1 and UE-29a#2 in upper Fortymile Canyon indicate that recharge has occurred more recently along major drainages.

Almost all hydrogen and oxygen isotopic data (pl. 5) indicate that recharge water was probably derived from melting snow. In addition, the data plot to the right of the Craig meteoric line (Craig, 1961). Whether this plot resulted from kinetic evaporative effects, as suggested by Claassen (1983), or because precipitation in Nevada during the glacial periods may have had a different isotopic composition than that of today, as suggested by A. F. White (Lawrence Berkeley Laboratory, written commun., 1982), is not known.

YUCCA MOUNTAIN HYDROGEOLOGIC SYSTEM

No long-term quantitative hydrologic data exist for Yucca Mountain; ongoing Nevada Nuclear Waste Storage Investigations studies must provide the basis for evaluating the suitability of the site as a geologic repository. The hydrologic system of Yucca Mountain and vicinity described here is based on information obtained from 1979 through mid-1983, principally from test holes in and around Yucca Mountain. Locations of wells, many of which are included in the monitoring network, are shown in figure 1 and plate 2. Well-construction data, land altitudes, recent measurements, and the most productive units (if known) are provided in table 8. Two series of holes were drilled to depths greater than a few hundred meters. In one series, small-diameter core holes were drilled to obtain stratigraphic, structural, and physical-property data (UE-25a#1, UE-25b#1, USW G-1, USW G-2, USW G-3/GU-3, and USW G-4). In the second series, holes were drilled principally to obtain hydrologic data; only a small amount of core was obtained (USW H-1, USW H-3, USW H-4, USW H-5, and USW H-6). Test holes UE-25b#1 and USW G-4 were cored and then reamed to allow for hydrologic testing. Tests include pumping tests with temperature and borehole flow surveys during pumping, and injection tests using packers to isolate test intervals. A series of shallower holes currently are being drilled to define hydraulic potential near Yucca Mountain.

Four piezometers were installed at different depths in USW H-1 to determine vertical-head gradients. Packers were placed in the lower part of some of the hydrologic test holes for long-term head measurements and to determine vertical gradients. These measurements were reported by Robison (1984).

Concepts on water movement within the unsaturated zone are not well-developed, in part because early hydrologic studies of Yucca Mountain concentrated on the saturated zone. Rocks in the unsaturated zone consist of: (1) Fractured, densely welded tuffs, with low matrix permeability and porosity; and (2) less-fractured nonwelded to partially welded and bedded tuffs, with higher matrix permeability and porosity. Because apertures of fractures are commonly greater than diameters of pores in the matrix, the matric potential in the matrix of unsaturated tuffs probably is much greater than that of the fractures. Under these conditions, water would not travel far in the fractures, if at all, before being drawn into the matrix. However, if the applied flux is greater than the matrix can transmit, even under a gradient of unity, water would begin flowing in the fractures, or perched-water zones would develop. Questions to be addressed include the following:

1. What is the rate of recharge, and how does it vary spatially and temporally?
2. Do the effects of capillary barriers inhibit movement of water from porous tuffs to fractures; if so, what potential gradients are necessary to initiate flow in fractures in densely welded tuffs?
3. If water moves in fractures, how far can it travel before being drawn into the matrix?
4. Does perched water occur in the unsaturated zone at Yucca Mountain?
5. What would be the effect of increased recharge that might accompany a return to pluvial climatic conditions on movement of water within the unsaturated zone? In particular, what effect would there be on travel time from a repository to the saturated zone?

Few data are currently available to answer these questions, and extensive studies are either underway or are being planned. These studies include: (1) Determination of matrix hydraulic properties from testing of cores; (2) in-situ measurement of matric potential and air pressure; (3) hole-to-hole transient pressure tests; and, if an exploratory shaft is

Table 8.--*Summary of data for observation wells in hydrologic network*

Well number	Location: Latitude	Location: Longitude	Altitude, in meters	Total depth, in meters	Outside diameter depth to bottom of casing, in centimeters x meters	Size of open hole below casing, in centimeters	Depth to water below land surface, in meters	Altitude of water surface above sea level, in meters	Most permeable saturated Member or unit (percent production, if known)
USW G-1	36°52'00"	116°27'29"	1,325.7	1,829	10.2 x 309.7	9.8	572.4	753.3	Tram/Bullfrog
USW G-2	36°53'22"	116°27'35"	1,553.9	1,830.6	6.0 x 242.3	7.6	524.2	1029.7	---------
USW G-3	36°49'05"	116°28'01"	1,480.2	1,533.4	14.0 x 791.9	10.1	607+1/	873+1/	---------
USW GU-3	36°49'04"	116°28'00"	1,248.8	804.7	8.9 x 539.8	7.6	----	----	---------
USW H-1	36°51'58"	116°27'12"	1,302.2	1,829	24.4 x 687.3	22.2	572.3 2/	729.7 2/	Prow Pass/Bullfrog
USW H-1									
PIEZO 4	36°51'58"	116°27'12"	1,302.2	572-640 3/	6.1 x 640 4/	----	572.2	730.0	Prow Pass
PIEZO 3	36°51'58"	116°27'12"	1,302.2	738-741 3/	4.3 x 741 4/	----	572.3 5/	729.9 5/	Bullfrog
PIEZO 2	36°51'58"	116°27'12"	1,302.2	1,112-1,115 3/	4.3 x 1,115 4/	----	568.5 5/	733.6 5/	Tram
PIEZO 1	36°51'58"	116°27'12"	1,302.2	1,805-1,806 3/	4.3 x 1,806 4/	----	519.0 5/	783.5 5/	Older ash-flow and bedded tuff
USW H-3	36°49'42"	116°28'01"	1,483.2	1,220	25.3 x 792.5	27.2	750.8	529.2	Tram (88); Lithic Ridge (10)
USW H-4	36°50'32"	116°26'54"	1,249	1,220	27.3 x 561	22.2	518.9	730.1	Tram (41); Bullfrog (38)
USW H-5	36°51'22"	116°27'55"	1,477	1,220	27.3 x 788	22.2	703.5+	773.6+	---------
USW H-6	36°50'49"	116°28'55"	1,306	1,220	27.3 x 581	22.2	526.0	780	---------
UE-25a#1	----------		1,198.7	762.3	15.8 x 746.8	7.6	469.3	729.4	---------
UE-25b#1	36°51'08"	116°26'23"	1,200.4	1,219.8	24.4 x 518.2	22.2	470.6	729.8	Bullfrog (49); Calico Hills (34)
USW VH-1	36°47'32"	116°33'07"	954.5	762	19.4 x 277.6	15.9	183.4	771.1	Bullfrog
UE-29a#1	36°56'29"	116°22'26"	1,215.1	65.5	76.2 x 10.7	66	27.7	1,187.4	
UE-29a#2	36°56'29"	116°22'26"	1,215.1	421.5	25.5 x 247.2	38.1	28.7	1,186.4	Calico Hills

1/ Hole not cleaned; measurement not reliable
2/ Isolated interval for piezometer tube
3/ Small diameter tubing
4/ Depth to water is still decreasing
5/ Composite water level

constructed, (4) detailed permeability testing of single boreholes and large-diameter tunnels and (5) sprinkler experiments to determine physics of flow within unsaturated, fractured tuffs.

Hypotheses on Controls of Saturated Hydraulic Conductivity

Two kinds of hydraulic conductivity occur in volcanic rocks: matrix and fracture. Hydrologic characteristics of various tuff units at Yucca Mountain are summarized in table 9. Both matrix and fracture hydraulic conductivity are related to size and interconnection of pathways for water movement. For example, tuffs can have high porosities (as much as 40 to 45 percent) but low-matrix hydraulic conductivities (1×10^{-9} cm/s), because pores are generally small and poorly connected. Hydrologically significant characteristics of fractures include number, orientation, and aperture. Number, orientation, and dimensions are related to rock type and structural setting; aperture is affected by depth, stress field, and rock strength, fluid pressure, and the presence or absence of fracture filling.

Claassen and White (1979) studied the possible extent of fracture control on the Rainier Mesa ground-water system; they concluded that the hydraulic characteristics of the Paintbrush Tuff are controlled by secondary (fracture) porosity. Blankennagel and Weir (1973) observed, through extensive hydrologic testing of rocks beneath Pahute Mesa, that welded tuff and rhyolite have higher permeabilities than nonwelded or bedded tuffs (fig. 4). Welded tuffs and rhyolite lavas are brittle and fracture readily. Nonwelded and bedded tuffs commonly contain fractures, but the fracture systems generally are less extensive. The interconnection of some of the fractures in the welded tuffs is demonstrated by hydrologic tests beneath Pahute Mesa and Yucca Mountain; these tests indicated that the volumes of water removed during pumping tests are many times the volumes of the fractures near the drill holes (Blankennagel and Weir, 1973; Rush and others, 1984).

Hydraulic conductivity may decrease with increasing depth below 1,600 m (fig. 4); welded tuffs are generally less permeable than rhyolites at the same depth. At greater depths, precipitation of minerals in fractures (commonly clays, silica, calcite, zeolites, or iron and manganese oxides), and (or) closing of fractures because of greater lithostatic stresses, tend to decrease the aperture of fractures. Hydraulic conductivity of fractures is proportional to the square of the aperture, and small decreases in aperture can have significant effects on fluid flow. As figure 4 indicates, the major effect of increasing depth is the absence of conductivities greater than 10^{-5} cm/s below depths of 1,600 m.

Controls on fracture density are not clear, but are complex. Besides being a function of rock type, fracture density is a function of structural setting. A zone of increased fracturing and faulting on the southeastern and eastern sides of Yucca Mountain has been mapped. Another feature evident from surface mapping is that fracture density decreases in the northern part of Yucca Mountain, where displacement and number of faults are less than in the southern part. Fracture density probably increases near faults of large displacement, but this hypothesis is untested.

Table 9.--*Preliminary summary of hydrologic characteristics of tuffs beneath Yucca Mountain and western Jackass Flats*[1/].

Stratigraphic unit	Dominant character	Thickness, in meters	Saturated matrix hydraulic conductivity, in centimeters per second	Porosity	Comments
Topopah Spring Member of Paintbrush Tuff.	Moderately to densely welded tuff.	330-380	8×10^{-10} to 6×10^{-7} (UE-25a#1)	0.03-0.30(J13) 0.10-0.28(USW H-1)	Unsaturated beneath Yucca Mountain; saturated beneath western Jackass Flats.
Tuffaceous beds of Calico Hills.	Zeolitized, nonwelded tuff; vitric tuff.	80-140	4×10^{-9} to 4×10^{-7} (UE-25a#1)	0.20-0.35(UE-25a#1) 0.45-0.48(USW H-1)	A productive zone in UE-25b#1; unsaturated in USW H-1, USW H-3; saturated in USW H-4, J-13.
Prow Pass Member of Crater Flat Tuff.	Nonwelded to moderately welded tuff, overlying bedded tuff.	90-155	3×10^{-8} to 2×10^{-6} (UE-25a#1)	0.10-0.30(UE-25a#1)	Unsaturated in USW H-3; saturated in USW H-4, UE-25b#1, J-13; unsaturated and saturated in USW H-1.
Bullfrog Member of Crater Flat Tuff.	Nonwelded to densely welded tuff, overlying bedded tuff.	120-160	2×10^{-7} to 2×10^{-6} (UE-25a#1)	0.15-0.25(UE-25a#1)	Lower 6 meters (bedded reworked tuff) most productive zone of UE-25a#1; unsaturated in USW H-3; saturated in USW H-1, USW H-4, UE-25b#1, J-13.
Tram Member of Crater Flat Tuff.	Nonwelded to moderately welded argillic, zeolitic ash-flow tuffs and bedded tuffs.	250-310	---	---	Saturated in USW H-1, USW H-3, UE-25b#1, J-13.
Flow breccia-----	Flow breccia, lava, bedded and ash-fall tuff.	0-120	---	---	Not present in USW H-3 or J-13; saturated in USW H-1, UE-25b#1.
Lithic Ridge Tuff and older tuffs.	Partially welded, argillic, zeolitic ash-fall tuff.	275-300	---	---	Saturated in USW H-1, USW H-3, UE-25b#1, J-13.

1/ Data from Anderson, 1981 (UE-25a#1); Rush and others, 1984 (USW H-1); Thordarson, 1983 (J-13).

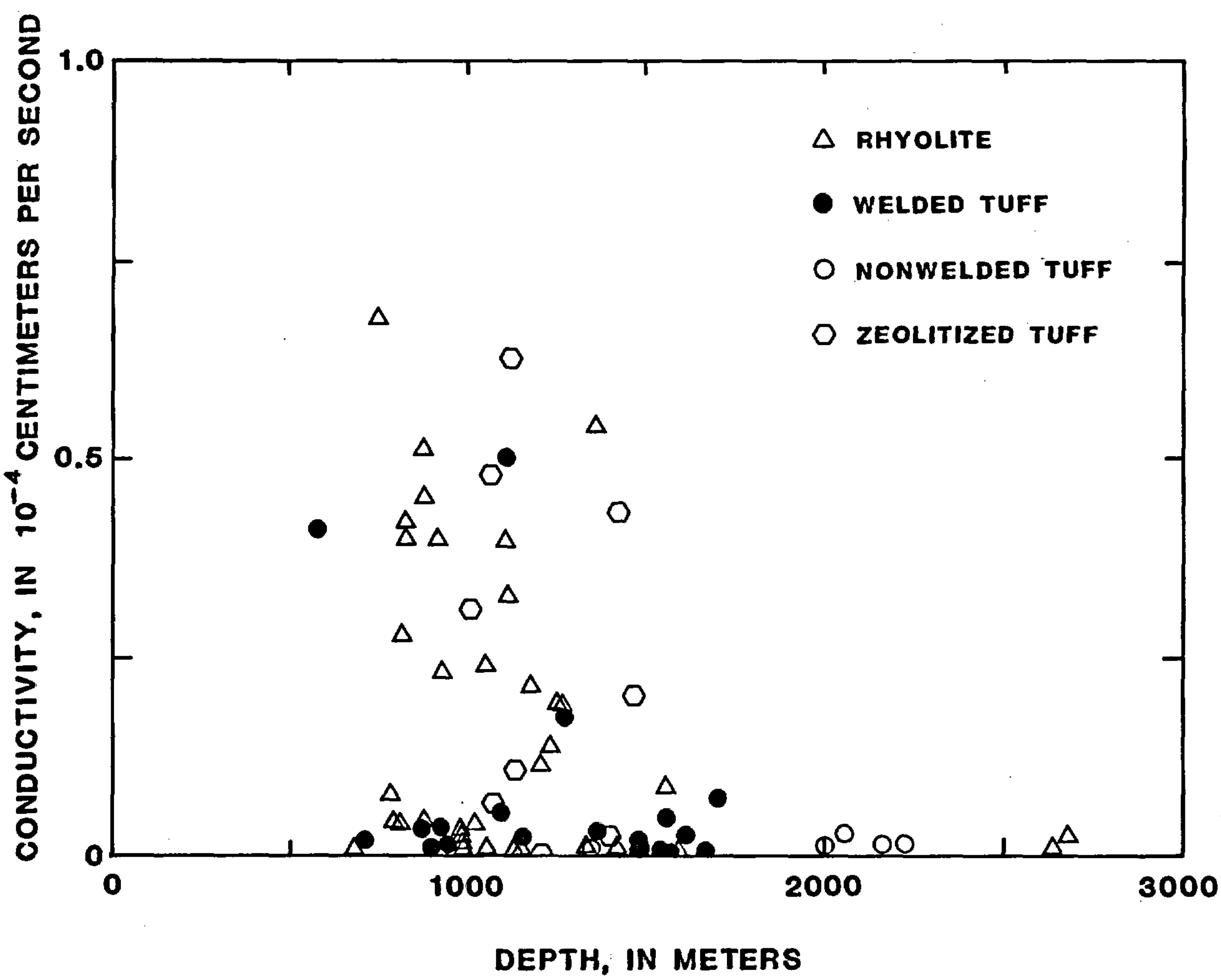


Figure 4.--Hydraulic-conductivity measurements in test holes beneath Pahute Mesa, as related to rock type and depth [Data from Blankennagel and Weir, 1973].

The importance of flow in fractures is indicated by two lines of evidence. First, hydraulic conductivity of the matrix, as measured on cores and by packer tests of nonproductive parts of drill holes, is much lower than in-situ conductivity measurements in productive parts of the drill holes. Second, productive zones, as determined by borehole-flow and temperature surveys performed during pumping tests, correlate with fracture zones determined from televiewer and caliper logs. Analysis of hydraulic-testing data, especially pumping and packer tests, is not complete; therefore, no in-situ measurements are reported. Nonetheless, preliminary interpretations indicate that conductivities of fractures are several orders of magnitude greater than matrix conductivities. Fractures at Yucca Mountain have preferred orientations (Scott and others, 1983); therefore, a high degree of anisotropy, with respect to hydraulic conductivity, probably also exists.

Structural settings at drill-hole sites affect both the in-situ hydraulic conductivity of the rocks and the geometric relationship between stratigraphic units and the saturated zone. For example, well J-13 (pl. 2) is in a relatively low-standing structural block, so part of the Topopah Spring Member is saturated. Unfaulted alluvium obscures locations and displacements of faults in underlying volcanic rocks, although Basin-and-Range-style faults with approximate north-south strikes are known to be present from nearby outcrops to the west. Northeast-trending strike-slip faults with left-lateral displacement may be present at, or just southeast of, well J-13 (Carr, W. J., U.S. Geological Survey, oral commun., 1983). High in-situ hydraulic conductivity of the Topopah Spring Member in well J-13 (Young, 1972; Thordarson, 1983) may be caused in part by the presence of these faults and associated fractures.

Hole USW H-3 was drilled where rocks penetrated in the hole would be relatively undisturbed by fracturing and faulting. This site was considered suitable for determining properties of the rock in a setting similar to settings expected in the repository. The Topopah Spring Member, tuffaceous beds of Calico Hills (hereafter generally shortened to the "Calico Hills unit"), Prow Pass Member, and most of Bullfrog Member are in the unsaturated zone at USW H-3. Analyses of hydrologic tests are not complete, but preliminary interpretations indicate that, the rock is much less permeable than rock in other drill holes.

USW H-4 was drilled on the eastern side of the block in a relatively unfractured area, just west of an area containing westerly dipping faults and fractures. Preliminary results indicate that hydraulic conductivities similar to those measured in UE-25b#1 exist, perhaps as a result of encountering westerly dipping fractures in the saturated zone.

Analysis of tests conducted to measure in-situ hydraulic conductivity of rocks in the saturated zone is underway, but it is incomplete, in part because a single unifying theory for analyzing aquifer tests for fractured rocks has not been developed sufficiently. However, borehole flow and temperature surveys conducted during pumping tests were used to determine the depth intervals that are productive in each drill hole. Results of straddle-packer tests later confirmed these determinations, although values for hydraulic conductivity are not yet available. These depth intervals are shown in figure 5.

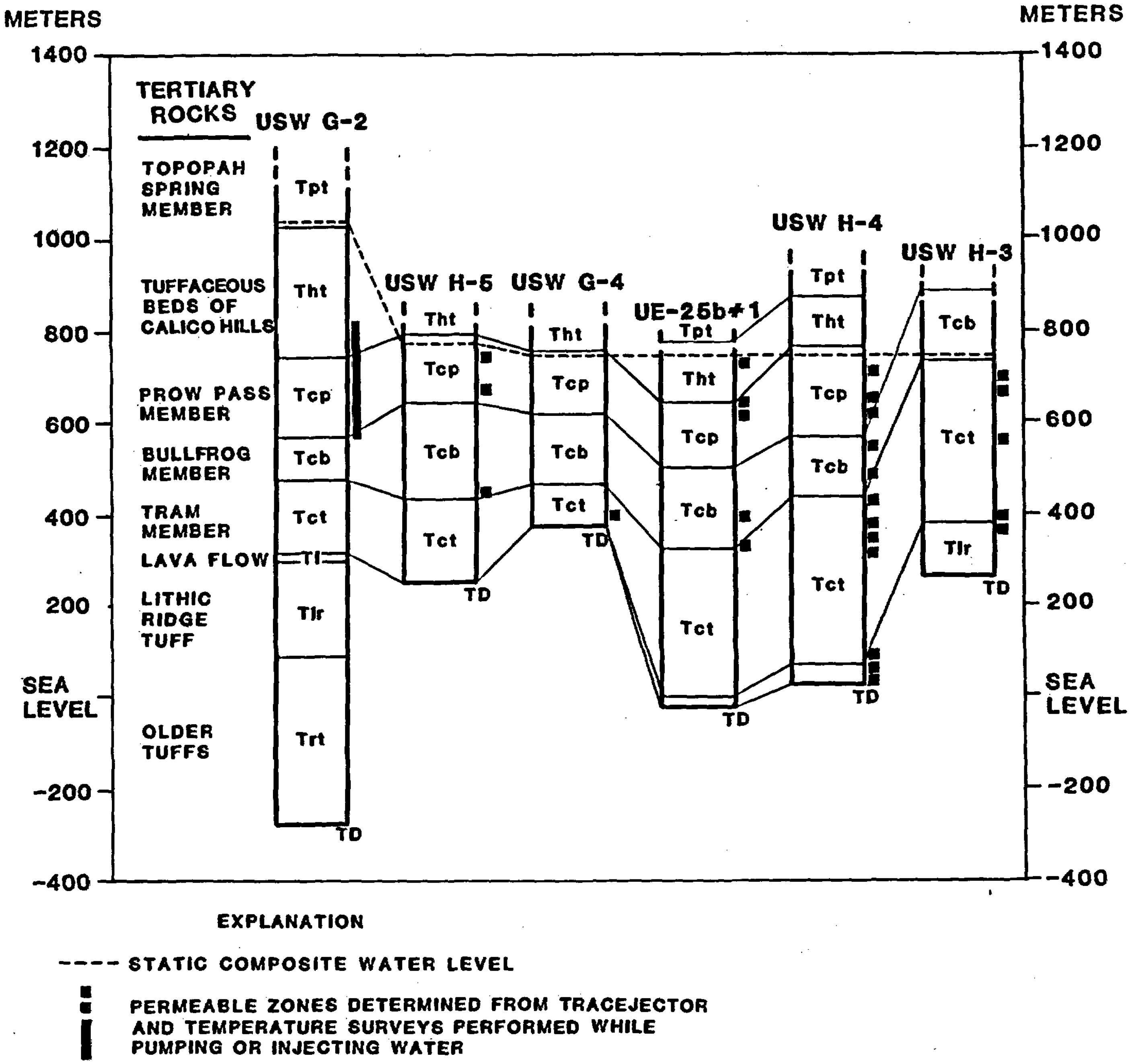


Figure 5.--Distribution of permeable zones in test holes near Yucca Mountain.

The variable occurrence of the productive zones shown in figure 5 indicates controls which stratigraphy may exert on distribution of production zones cannot be readily established from available data. As discussed earlier, hydraulic conductivity of fractures in the tuffs in the vicinity of the Nevada Test Site (and, therefore, the relative contribution of fractures to the productivity of drill holes) is much greater than the conductivity (or contribution) of the rock matrix. As a result, production intervals in a drill hole are determined by the depths at which the hole intercepts saturated transmissive fractures that are connected to other such fractures. Because dip of the fractures is generally steep (70 to 85°), fracture planes are nearly parallel to nearly vertical drill holes; the resulting bias against intercepting many fractures means that many vertical drill holes would have to be drilled before a statistically significant number of transmissive fractures could be tested. Conclusions regarding stratigraphic control of conductivity are not technically appropriate at this time; the following remarks about hydraulic properties of these units are generalized and preliminary.

Saturated permeability of the Topopah Spring Member of the Paintbrush Tuff is probably the greatest of any unit in the volcanic section beneath Yucca Mountain; however, the unit mostly is above the water table. Many fractures have been observed in core and television surveys. Lithophysal cavities are common in some zones (Scott and others, 1983). Lost circulation problems are common while drilling through the Topopah Spring Member. Matrix permeability of densely welded parts of the unit is low. In well J-13, the Topopah Spring unit is in the saturated zone; it is the most productive unit in the section penetrated by the drill hole (Thordarson, 1983).

In well UE-25b#1, the Calico Hills unit is the second most productive unit in the section penetrated by the drill hole. Because this unit has a low matrix hydraulic conductivity (probably due to its high zeolite content) in UE-25a#1 (about 100 m away), the large production probably is due to fractures related to the north-trending normal faults or northwest-trending shear fractures that occur nearby. Hydrologic properties of the Calico Hills unit elsewhere beneath Yucca Mountain are not known, either because the unit is in the unsaturated zone, or because analysis of testing data is not complete.

The Prow Pass and Bullfrog Members of the Crater Flat Tuff are similar in hydrologic properties. Their matrix conductivities are higher than those of the Calico Hills unit and the Topopah Spring Member, and their in-situ conductivities are controlled by fractures. These two units commonly are the most productive ones penetrated by the drill holes in Yucca Mountain.

Units underlying the Bullfrog Member are generally less productive, although exceptions occur. For example, almost all production from USW G-4 was from the Tram Member.

A simplistic model describing hydraulic characteristics of the stratigraphic units underlying Yucca Mountain can be developed, based upon division of the units into: (1) Moderately and densely welded tuffs; and (2) nonwelded and bedded tuffs. Moderately and densely welded tuffs are characterized by relatively low porosities (5 to 25 percent) (Anderson, 1981; Lappin and others, 1981), a tendency to fracture easily, and low-matrix conductivities. Water movement generally is along fractures, rather than through the matrix. In nonwelded and bedded tuffs, porosities are higher (greater than 30 percent) and the tendency to fracture is less, although fractures do occur. Unless the rock is altered and contains clays or zeolites, matrix conductivities are generally higher than in the welded tuffs. Water movement occurs in the matrix, but it also may be significant in fractures.

This model provides a starting point for predicting hydraulic properties beneath Yucca Mountain, but requires knowledge of the welding characteristics and extent of secondary mineralization of the units. The Tiva Canyon and Topopah Spring Members are predominantly moderately to densely welded tuffs. The Crater Flat Tuff (Prow Pass, Bullfrog, and Tram Members) contain partially to moderately welded tuffs. The Yucca Mountain and Pah Canyon Members, tuffaceous beds of Calico Hills, and Lithic Ridge Tuff are predominantly nonwelded and bedded tuffs. In addition, bedded tuffs commonly separate ash-flow tuff units. Zeolitization and argillization have occurred in most units beneath the densely welded part of the Topopah Spring Member. The Calico Hills unit, in particular, is highly zeolitized in the northern part of Yucca Mountain, so its permeability probably is low there. Rocks beneath the Tram Member generally exhibit low permeabilities, because of either mineralization or high lithostatic pressures.

Ground-Water Flow

Recharge Rates

Distribution of recharge is a function of amount and distribution of precipitation, type of precipitation, conditions at time of snowmelt (if a snowpack is present), lithology and moisture content of soil, vegetation, and topography. Interaction of these factors is complex, and data on distribution of recharge at Yucca Mountain do not exist. One hypothesis is that more recharge occurs beneath washes than beneath surrounding ridges, because water is concentrated in washes during runoff events. However, alluvium in washes may store the water at a shallow depth until evaporative mechanisms become active again after the storm has passed and humidity has decreased. A second hypothesis is that water that is intercepted by open fractures in surficial bedrock may move rapidly to a depth where evaporative forces are very small, and it may actually contribute more to total recharge than water that infiltrates beneath washes.

Total downward flux in the unsaturated zone at Yucca Mountain must be low, because of the arid climate and small drainage areas. Data presented by Winograd (1981) enable calculation of flux through unsaturated alluvium in Yucca Flat, in the Nevada Test Site 45 to 50 km northeast of Yucca Mountain, to be about 5×10^{-4} $m^3/yr/m^2$ of land surface, or about 0.5 mm/yr. Annual precipitation at Yucca Mountain and Yucca Flat is approximately the same (100 to 150 mm). Because of the difference in lithology of the rock at the land surface (welded tuff versus alluvium), and the difference in slope (steep versus almost horizontal), unsaturated-zone flux at Yucca Mountain probably is different from that beneath Yucca Flat, but probably is still very small.

The saturated matrix conductivity of the welded tuffs is small--less than 10^{-6} cm/s, and as low at 10^{-9} cm/s (table 9). The geometric-mean saturated hydraulic conductivity of cores from the Topopah Spring Member from well UE-25a#1 (Anderson, 1981) is approximately 9.5 x 10^{-9} cm/s. Matric tensions have been estimated at 1 to 2 bars, based on mercury-injection test data from core from USW H-1. Hydraulic conductivities under these tensions are probably two to three orders of magnitude smaller than saturated values (Weeks and Wilson, 1984); thus, hydraulic conductivity reasonably can be assumed to be about 10^{-10} cm/s. Assuming an average gradient of unity (tensions are relatively uniform throughout the Topopah Spring Member, so that the principal component of the gradient is due to position), fluxes in the unsaturated matrix could be on the order of 10^{-10} $cm^3/s/cm^2$ of land surface, or 0.03 mm/yr or less, about an order of magnitude smaller than that calculated for Yucca Flat. This difference suggests either that flux through the unsaturated zone is lower at Yucca Mountain than at Yucca Flat, or, that an additional but undetermined amount of flux travels along fractures at Yucca Mountain.

Flow of heat within rocks is by both diffusion and advective mechanisms. Because heat can be transported by moving water in both the unsaturated and saturated zones, temperature profiles can be sensitive indicators of water movement. J. H. Sass (U.S. Geological Survey, written commun., 1983) provided the following summary of his heat-flow studies pertaining to recharge at Yucca Mountain.

> "Temperature profiles from drill holes near Yucca Mountain are shown on [figure 6]. The static water level beneath Yucca Mountain is about 500 m. Thus, there is evidence for hydrologic disturbance to the temperature field, both above and below the water table....Some, but probably not all, of the variations in gradient for this series of holes may be explained in terms of long-lived temperature changes caused by loss of large quantities of mud during drilling. However, the holes are effectively in thermal equilibrium and the gradient variations cannot be ascribed plausibly to variations in thermal conductivity (particularly where there are temperature reversals).
>
> For the deepest holes (USW G-1 and USW H-1) [figure 6], systematic variations in temperature gradient occur without corresponding variations in thermal conductivity. Preliminary interpretation suggested a systematic downward percolation of groundwater through both unsaturated and saturated zones with seepage velocities of a few millimeters per year. With sufficient thermal conductivity data now available, that interpretation can be tested quantitatively.
>
> Temperature gradients within individual formations were combined with thermal-conductivity determinations by Lappin and others (1981) (above 900 m), and [Sass and Lachenbruch (1982)] (below 900 m), to obtain component diffusive heat flows for each formation (Sass and Lachenbruch, 1982). Diffusive heat flow in USW G-1 increases systematically with depth [fig. 7], lending support to the preliminary interpretation. If one-dimensional steady-state vertical water flow is assumed to be responsible for the observed increase in heat flow with depth, a simple calculation can be made to estimate seepage velocity and penetration depth of vertical water flow. This calculation (Sass and

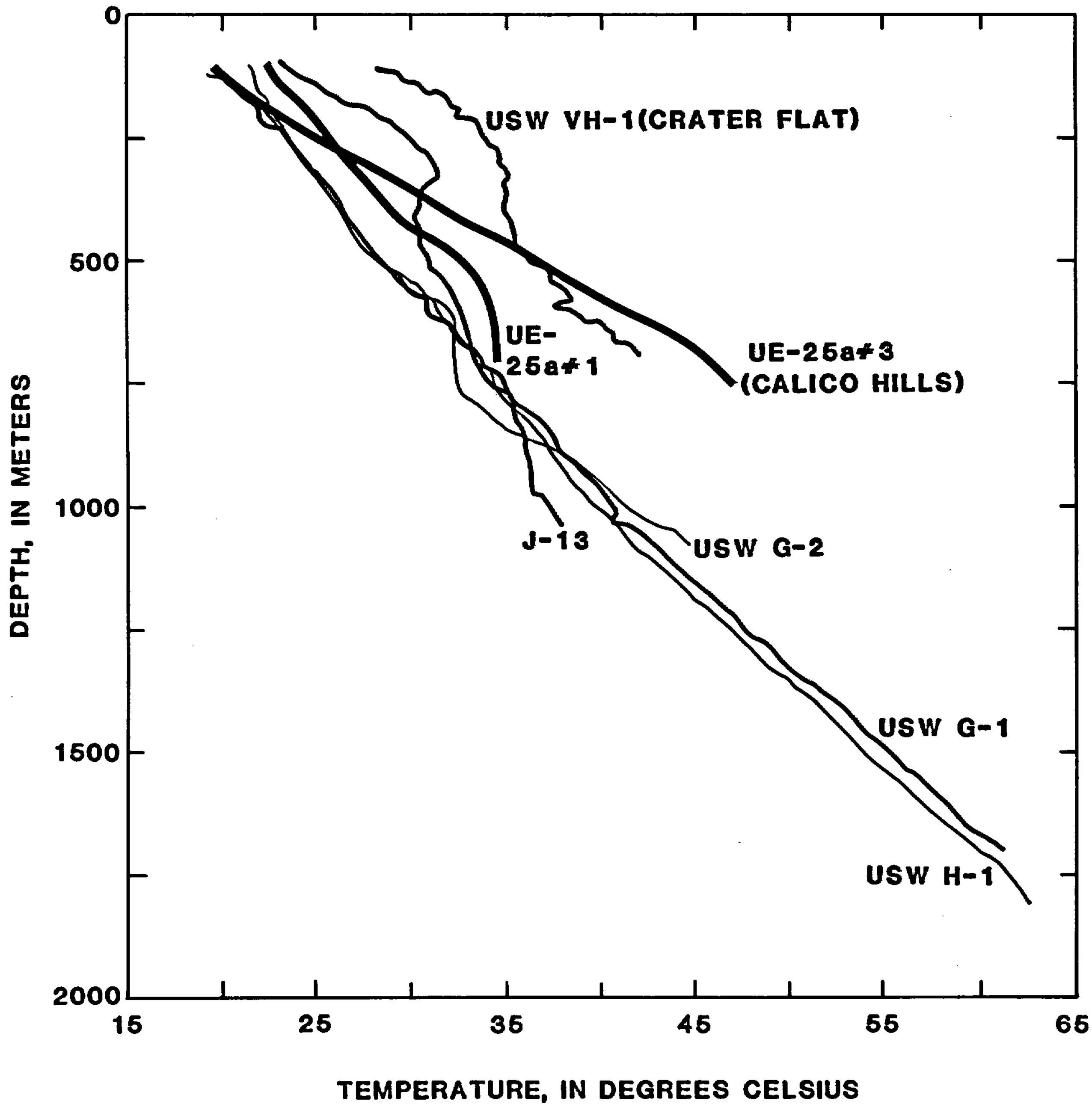
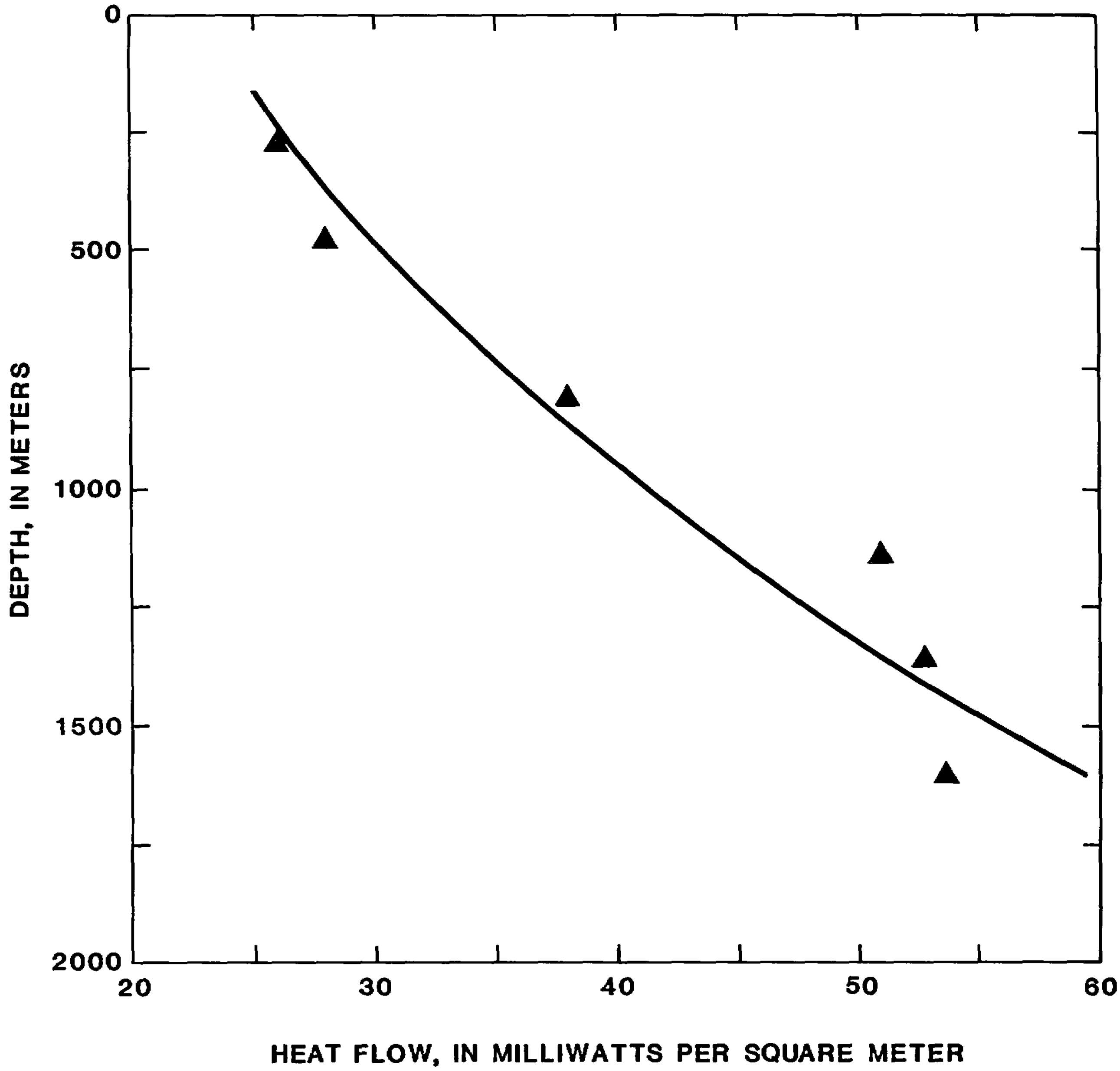


Figure 6.--Temperatures in drill holes deeper than 600 meters for Yucca Mountain and nearby areas [Modified from Sass and Lachenbruch, 1982].



NOTE: SOLID LINE REPRESENTS THE LEAST-SQUARES REGRESSION LINE OF THE FORM $q=q_0 exp(-Az)$, WHERE q_0 IS SURFACE HEAT FLOW AND A IS PROPORTIONAL TO THE SEEPAGE VELOCITY (POSITIVE UPWARDS).

Figure 7.--Heat flow as a function of depth for test well USW G-1 [From Sass and Lachenbruch, 1982].

Lachenbruch, 1982, equations 1 through 7) resulted in an estimate of 8 mm/yr for vertical seepage velocity in both the unsaturated and saturated zones."

This analysis includes data from only one drill hole; other models could describe the variation in heat flow noted. Sass's heat-flow studies are being continued; they are expected to provide a very useful tool for the study of water movement beneath Yucca Mountain.

In summary, the amount of recharge that occurs at Yucca Mountain and its spatial and temporal distribution are not known. Arid environment at Yucca Mountain and absence of large drainage basins indicate that recharge is very small. Data from Yucca Flat substantiate this assertion. Long-term-average recharge rates are probably less than 5 mm/yr, and perhaps much less. Recharge may occur in pulses (as suggested by Sass's observations in UE-25a#7), rather than constantly over a long period of time.

Potentiometric Levels and Head Relationships

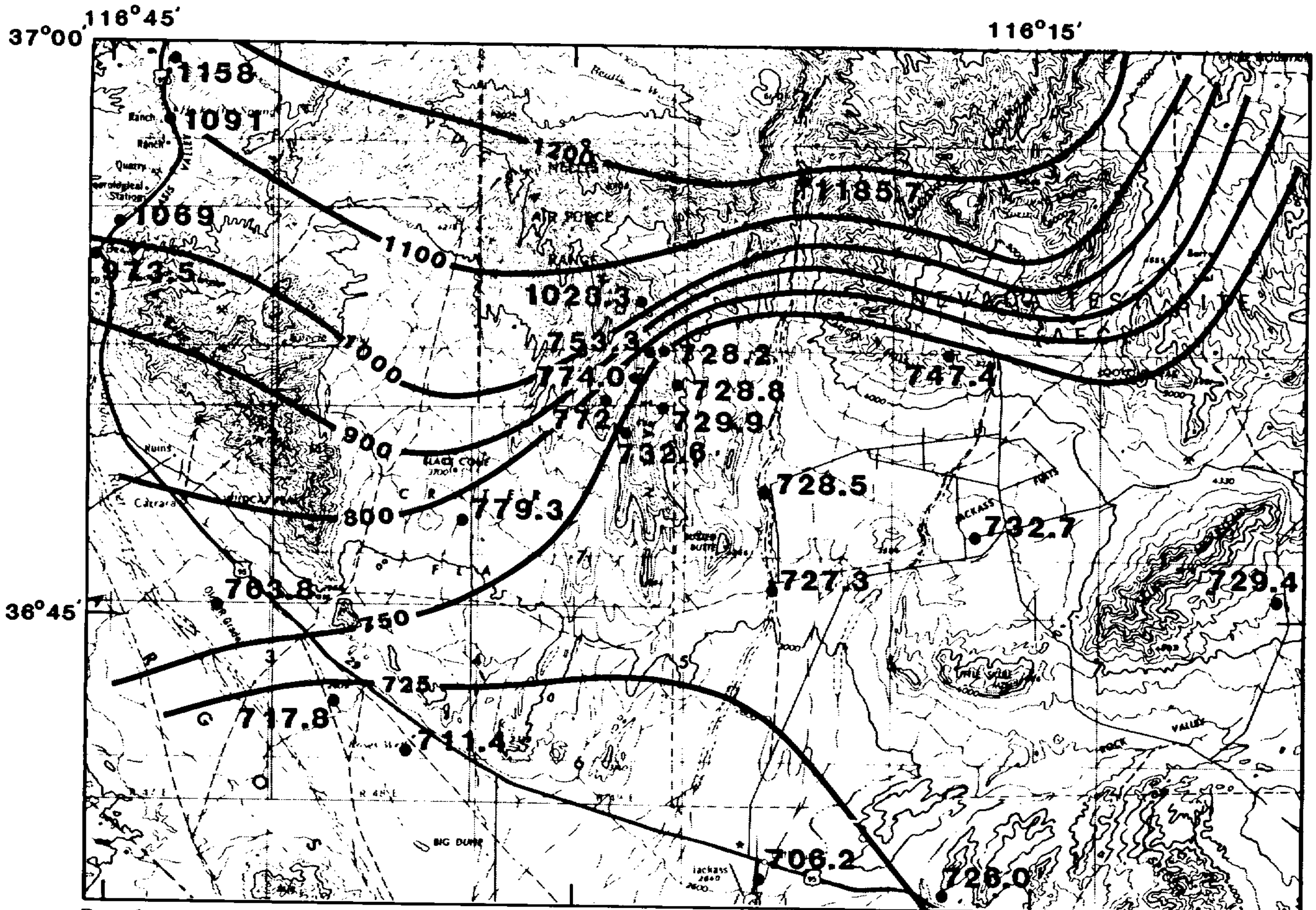
Measured head values used to construct the potentiometric map (fig. 8) represent composite water levels, which, in effect, are weighted averages of hydraulic heads in boreholes. Weighting is proportional to hydraulic conductivity of the rock. In USW H-1, for example, even though an abnormally high head was measured near the bottom of the borehole (table 8), hydraulic conductivity of the rock at that depth was much smaller than it was higher in the hole (Rush and others, 1984), so measured composite head is very similar to the head in zones of higher hydraulic conductivity.

Two contour intervals are shown in figure 8, because of the large range in gradients; the gradient is low in western Jackass Flats (Fortymile Wash area) and in the Amargosa Desert; the gradient is high in volcanic rocks north of Yucca Mountain and across northern Yucca Mountain. Steep gradients that cross parts of Yucca Mountain indicate that low-permeability rocks are present in the saturated zone beneath parts of the site. Their nature or origin is unknown.

Data presently are insufficient to determine the range of seasonal fluctuations in potentiometric levels. These fluctuations are believed to be small, because of the great depth to water (approximately 500 m) and the small amount of recharge. Small changes in depth to water occur, because of barometric-pressure changes and earth tides.

The vertical component of flow in the saturated zone is not well-known. Potentiometric data collected in conjunction with injection testing generally are not adequate to define vertical head gradients. Measurements of potential in more permeable rocks are very similar to composite heads. However, in low-permeability rocks, these heads may require weeks or months to stabilize, so measurements made during short-term tests are unreliable.

Temperature logs have been used to estimate flow directions and rates of flow in boreholes. However, use of these techniques has several potential problems. First, transient effects from drilling and pumping or injecting water still may be present at the time of the survey. Second, most proce-



Base from U.S Geological Survey 1:250,000, Death Valley, California; Nevada, 1970. Topographic contour interval 200 feet.

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

—800— POTENTIOMETRIC CONTOUR--
Shows altitude of potentiometric surface, 19--.
Contour interval, in meters, is variable.
Datum is sea level.

•747.4 TEST HOLE--
Number is measured composite water level, in meters above sea level.

Figure 8.--Preliminary potentiometric surface of site vicinity.

dures assume that heat moves only vertically, and, therefore, that a one-dimensional continuity equation is valid. If a horizontal component of ground-water flow is present, then this assumption may not be valid. Third, flow rates that may be calculated in the saturated zone are greater than those that actually occur in undisturbed rock, because of very high permeability within the borehole.

Temperatures in many boreholes in the Yucca Mountain area indicate that downward flow occurs in the upper part of the saturated zone. Downward flow causes an increase in thermal gradient with increasing depth. In the lower part of some boreholes (USW H-1, USW G-2) the thermal gradient slightly decreases with increasing depth, indicating very slow upward flow (Sass and Lachenbruch, 1982). This decrease suggests that, in the lower parts of the holes, hydraulic head increases with depth.

Additional evidence for upward flow in USW H-1 is presented in table 8. Preliminary head data from four piezometers cemented in USW H-1 indicate that head at a depth of 1,806 m is about 50 m higher than in the upper three piezometers, which have heads very similar to the composite head, determined prior to installing the piezometers (Robison, 1984). Vertical gradient between the two lower piezometers is 0.07, which is much greater than the horizontal composite gradient (0.00016) between USW H-1 and J-13.

Well UE-25p#1, east of Yucca Mountain, was drilled in 1983 to a depth of 1,805 m, and it penetrated pre-Tertiary carbonate rocks at a depth of about 1,250 m. The hydraulic head in carbonate rocks is 20 m higher than in overlying Tertiary rocks.

Explanations of these data are tentative, because temperature profiles and reliable head data for low-permeability zones are available only for a very few holes. At first, it may appear anomalous for both upward and downward water movement to occur in a borehole, and (because hydraulic head in the rock controls direction of fluid movement in the borehole) in the surrounding rock.

Upward flow (albeit very slow) may be caused by the position of Yucca Mountain in the ground-water basin. Simple models of ground-water basins consist of an area where recharge occurs (vertical flow is downward), and where discharge occurs (vertical flow is upward). In intermediate areas, flow is transitional from downward, to strictly horizontal, to upward. Although the Alkali Flat-Furnace Creek Ranch subbasin is not simple, these concepts generally are still valid. Present-day recharge areas are north of Yucca Mountain; discharge areas are far to the south. Thus, Yucca Mountain is in an area where vertical flow related to the regional flow system may be in either direction; data indicate that hydraulic gradient in deeper rocks is upward.

Downward movement of water in upper parts of the saturated section (indicated by temperature logs) may be caused by small amounts of recharge at Yucca Mountain. The depth at which vertical flow ceases, and all flow is horizontal, is a complex function of the amount of recharge, position in the regional flow system, and distribution of hydraulic conductivity beneath Yucca Mountain; therefore, it is variable and generally unknown.

An alternative hypothesis is that direction of flow is related to distribution of hydraulic conductivity in the section. The low hydraulic gradient between Drill Hole Wash, the eastern side of Yucca Mountain, and Fortymile Wash indicates that hydraulic connectivity of these permeable rocks is good. Permeable sections would, therefore, have the lowest head in the section, and they would act as drains for the ground-water system beneath Yucca Mountain. Water could flow both upward and downward to these drains, and then flow laterally toward Fortymile Wash. Local recharge would increase the amount of downward flow in the upper part of the saturated zone.

Flow Paths from Yucca Mountain to Natural Discharge Areas

Potentiometric levels indicate general directions of ground-water flow, and, therefore, potential directions of movement of radionuclides from a repository beneath Yucca Mountain. In general, flow beneath Yucca Mountain probably is toward the southeast into the Fortymile Wash area, and then to the south toward the Amargosa Desert and Alkali Flat, and beyond to Furnace Creek Ranch (pl. 3). The actual flowpath of a water particle moving from Yucca Mountain may be much different from that indicated by contour lines, as dictated by such conditions as anisotropy, the location of permeable fractures in the saturated zone, and the possible occurrence of gouge along faults.

Whether much of the discharge at Furnace Creek Ranch comes from the alluvium beneath the Amargosa Desert is uncertain. The steep gradient that probably occurs between Death Valley Junction and Furnace Creek Ranch, across carbonate rocks, which typically are very transmissive, indicates that two separate flow systems may be involved. Another possible source of discharge water at Furnace Creek Ranch is underflow from the Ash Meadows subbasin through Paleozoic rocks that presumably underlie the alluvium. Water-chemistry data are of limited use in determining the source of the water also discharging at Furnace Creek Ranch. In summary, most water flowing beneath Yucca Mountain would be discharged at Alkali Flat; some may discharge at Furnace Creek Ranch.

Flow Velocities

In the unsaturated zone, the dominant transporting medium in densely welded tuffs is either matrix or fractures. If water primarily moves through the fractures, velocities may be quite high for short periods of time, although long-term average velocity would be low. If flow in the matrix is dominant, velocities would be slow, because of low hydraulic conductivity and high effective porosity. A low recharge rate, perhaps 1 mm/yr or less, is necessary for matrix flow to dominate over fracture flow.

Although more data are available for the saturated zone, and the physics of flow is much simpler, flow velocities still are poorly known. Preliminary calculations of travel times between Yucca Mountain and the accessible environment (assumed to be 10 km downgradient) range from tens to thousands of years, depending on which values of effective porosity, hydraulic conductivity, and hydraulic gradient are used.

Carbon-14 data possibly could be used to determine flow velocities from Yucca Mountain to Fortymile Wash. However, mixing of water of different ages and the possibility of "contamination" of ground water by recharge events occurring beneath intermittent streams, such as Fortymile Wash, make such calculations complex and uncertain because of the large number of variables.

Carbon-14 data can be used to place limits on saturated-zone velocities upgradient of Yucca Mountain. Waters beneath Yucca Mountain have ages of about 12,000 to 17,000 years (table 10). Distance to present-day recharge is about 65 km. If no appreciable mixing with waters younger or older occurs, the water has traveled with an average velocity of about 3.5 to 5.5 m/yr. If recharge occurred closer to Yucca Mountain, average velocity would be less. If mixing with younger water has occurred after recharge, actual average velocity also would be less than calculated. Mixing with appreciable amounts of older water is unlikely; if older water is still present, it would be moving too slowly for much dilution to occur. A mixture of 20 percent carbon-14 "dead water" (more than 50,000 years old) and 80 percent 10,000-year-old water could have an apparent age of about 11,800 years; thus if the unmixed water is actually only about 10,000 years old, a velocity of 6.5 m/yr results. Because most rocks upgradient are tuffs and rhyolites that presumably have effective porosities similar to tuffs beneath Yucca Mountain and western Jackass Flats, velocities within the volcanic rocks downgradient are probably similar to those upgradient, because mass must be preserved. Velocities will be somewhat greater downgradient, because additional water is contributed from other areas. These calculations assume that dissolved carbonate species, especially bicarbonate ions, are conservative, and that they move at the same rate as water does.

Hydrochemistry

Samples of ground water were collected principally during pumping tests of the entire saturated interval penetrated by the drill hole (except as noted in table 10); results were summarized by Benson and others (1983). Dissolved constituents were primarily sodium and bicarbonate. The pH ranges from 7 to 8. Dissolved-solids concentration is typically about 300 mg/L; chemistry of the water beneath Yucca Mountain appears to be derived solely by reaction with tuffaceous rocks.

Minor differences in composition occur from well to well; whether these differences are significant or are caused by measurement error is not known. Carbon-14 contents for samples from Yucca Mountain are equivalent to ages (uncorrected for dead carbon) ranging from 12,000 to 17,200 years. Samples from wells J-12 and J-13 (near Fortymile Wash, east and downgradient from Yucca Mountain) yielded uncorrected carbon-14 ages of 9,100 and 9,900 years. Water from two samples from different zones in UE-29a#2, approximately 15 km north of J-13 in Fortymile Canyon, was approximately 4,000 years old. These results and potentiometric data indicate that water from J-12 and J-13 may be either a mixture of water from Yucca Mountain and Fortymile Canyon, or a mixture of these waters with water that was recharged from Fortymile Wash near J-12 and J-13. Data are not sufficient to make this distinction.

Table 10.--*Chemical composition of water samples obtained from wells in the Yucca Mountain area*[1/]

[δD, del deuterium, reported in parts per thousand, o/oo, relative to SMOW, standard mean ocean water; $\delta^{18}O$, del oxygen-18, reported in parts per thousand, o/oo, relative to standard mean ocean water; $\delta^{13}C$, del carbon-13, reported in parts per thousand relative to PDB, Peedee belemnite; ^{14}C, carbon-14; yr B.P., years before present, HTO, tritium, reported in picocuries per liter; °C, degrees Celsius; dissolved constituents: Ca (calcium), Mg (magnesium), Na (sodium), K (potassium), HCO_3 (bicarbonate), Cl (chloride), SO_4 (sulfate), SiO_2 (aqueous silica), and F (fluoride) reported in milligrams per liter, excepting Li (lithium) and Sr (strontium) which are reported in micrograms per liter; - (dash) indicates entire well bore pumped in the case of column five data, otherwise, - (dash) indicates that no data are available for particular analysis of interest.]

Well number	Land-surface altitude, in meters	Approximate well depth, in meters	Approximate depth to water, in meters	Interval sampled, in meters	Collection date	δD o/oo SMOW	$\delta^{18}O$ o/oo SMOW	$\delta^{13}C$ o/oo PDB	^{14}C percent modern	^{14}C apparent age (yr B.P.)	HTO
UE-25b#1	1,200.4	1,220	470	---	08/07/81	- 99.5	-13.4	-10.8	---	---	---
UE-25b#1				---	09/01/81	-101	-13.4	-10.4	16.7	14,400	<200
UE-25b#1				(853-914)	07/20/82	- 99.5	-13.5	- 8.6	18.9	13,400	2
UE-29a#2	1,215.1	422	29	---	01/08/82	- 93.5	-12.8	-12.6	62.3	3,800	37
UE-29a#2				---	01/15/82	- 93.0	-12.8	-13.1	60.0	4,100	37
USW G-4	1,270.0	915	541	---	12/09/82	-103	-13.8	- 9.1	22.0	12,160	---
USW H-1	1,302.2	1,829	572	(572-687)	10/20/80	-103	-13.4	---	19.9	13,000	< 20
USW H-1				(687-1,829)	12/08/80	-101	-13.5	-11.4	23.9	12,000	< 20
USW H-4	1,249.0	1,220	519	---	05/17/82	-104	-14.0	- 7.4	11.8	17,200	< 10
USW H-5	1,477.8	1,220	704	---	07/03/82	-102	-13.6	-10.3	18.2	13,700	<200
USW H-5				---	07/26/82	-102	-13.6	-10.3	21.4	12,400	<200
USW H-6	1,306.1	1,220	526	---	10/16/82	-106	-13.8	- 7.5	16.3	14,600	< 10
USW VH-1	954.5	726	184	---	02/06/81	----	-----	-----	----	------	---
USW VH-1				---	02/08/81	----	-----	-----	----	------	---
USW VH-1				---	02/11/81	-108	-14.2	- 8.5	12.2	17,000	< 20
J-12	953.5	347	225	---	03/26/71	- 97.5	-12.8	- 7.9	32.2	9,100	<220
J-13	1,011.3	1,063	282	---	03/26/71	- 97.5	-13.0	- 7.3	29.2	9,900	<220

Table 10.--*Chemical composition of water samples taken from wells in the Yucca Mountain area*[1/].--Continued

Well number	Onsite pH (units)	Laboratory pH (units)	Water temperature (°C)	Dissolved constituents											
				Ca	Mg	Na	K	HCO_3 onsite	HCO_3 laboratory	Cl	SO_4	SiO_2	Li	Sr	F
UE-25b#1	7.1	6.8	36.0	19	0.73	53	3.7	173	158	13	24	53	950	44	1.5
UE-25b#1	7.5	7.5	36.0	17	.59	46	3.5	139	134	8.5	22	52	220	38	1.6
UE-25b#1	7.1	7.7	37.2	18	.72	46	2.8	133	138	7.5	21	51	120	47	1.6
UE-29a#2	7.2	7.6	25.1	10	.2	44	1.1	107	112	11	22	44	100	39	1.0
UE-29a#2	7.0	7.4	22.7	10	.3	44	1.3	107	110	8.8	21	44	110	33	.9
USW H-1	7.7	7.8	33.0	4.5	<.1	51	2.4	---	115	5.7	18	47	40	5	1.2
USW G-4	7.7	7.5	35.6	13	.2	57	2.1	139	143	5.9	19	45	67	17	2.5
USW H-1	7.5	8.6	34.7	6.2	<.1	51	1.6	---	122	5.8	19	40	40	20	1.0
USW H-4	7.4	7.9	34.8	17	.29	73	2.6	173	171	6.9	26	46	130	27	4.8
USW H-5	7.8	7.8	36.5	1.9	.01	60	2.1	126	124	6.1	16	48	62	9	1.4
USW H-5	7.9	8.0	35.3	2.0	<.01	60	2.1	127	124	6.1	16	48	71	4	1.4
USW H-6	8.1	8.3	37.8	4.1	.09	86	1.3	182	188	7.6	29	48	82	8	4.7
USW VH-1	7.9	8.0	35.2	11	1.6	79	1.9	167	158	11	44	50	90	70	2.7
USW VH-1	7.5	7.9	35.5	10	1.5	80	1.9	165	158	10	45	50	90	70	2.7
USW VH-1	7.5	8.0	35.5	9.9	1.5	78	1.8	162	158	10	44	49	90	60	2.7
J-12	7.1	---	27.0	14	2.1	38	5.1	---	119	7.3	22	54	40	10	2.1
J-13	7.2	---	31.0	12	2.1	42	5.0	---	124	7.1	17	57	40	20	2.4

1/ Benson and others, 1983

SUMMARY AND CONCLUSIONS

The current understanding of surface and subsurface hydrology of the Candidate Area and the site addressed in this report is based on available literature and preliminary site-exploration activities through mid-1983. The Candidate Area covers a major part of the Death Valley Basin Hydrographic Region of California-Nevada and a small part of the Central Hydrographic Region of Nevada (including parts of California). The Death Valley Basin in Nevada drains into Death Valley in California via the Amargosa River and its tributaries, whereas the Central Region is characterized in the Candidate Area by closed basins containing playas.

The Candidate Area is one of the most arid regions of the United States. The climate is typified by low rainfall, low humidity, high evaporation, high summer temperature, and high wind velocities during the spring. Precipitation generally increases with altitude; average annual amounts range from 43 mm in Death Valley to 760 mm on the highest peaks of the Spring Mountains.

Because of generally arid climatic conditions, no perennial streams exist in the Candidate Area. Perennial surface water is restricted to short reaches of the Amargosa River, small pools at some large springs, and marshes in Alkali Flat and Death Valley. However, arroyos in the Candidate Area occasionally flood during severe convective rainstorms. Long-term flood records are few; however, predictions of flood magnitudes and frequencies indicate that occasional flash floods and debris flows are anticipated.

Regional hydrogeologic units in the Candidate Area include the lower clastic aquitard, lower carbonate aquifer, upper clastic aquitard, upper carbonate aquifer, volcanic aquifers and aquitards, alluvial aquifers, and lacustrine aquitards. Normal and strike-slip faults have juxtaposed rocks of differing hydraulic properties, creating a complex hydrologic setting.

An average of 100 to 150 mm of precipitation falls annually on the site. Most of that evaporates, leaving little water available for recharge. The resulting flux of water through the unsaturated zone probably is less than 5 mm/yr, and likely much less. Water in the Topopah Spring Member at Yucca Mountain, the proposed repository host rock, probably flows vertically downward until it reaches the water table, although perched-water zones may occur.

Velocity of flow and resulting travel time in the unsaturated zone strongly depend on effective porosity and hydraulic conductivity of fractures and rock matrix. This porosity is not known at present. Hydraulic conductivity in unsaturated rocks depends on the degree of saturation, and this parameter is not well defined.

The lateral direction of ground-water movement in the saturated zone of the site and its vicinity is probably to the southeast, but it may be to the south. The gradient is variable within the site. Ground-water velocities in the saturated zone are insufficiently known. Determining these velocities depends mostly on better definition of hydraulic conductivity and effective porosity.

CURRENT STUDIES

Studies to define the hydrology of the saturated and unsaturated zones at Yucca Mountain are continuing. Exploratory drilling is being used to define better the distribution of hydraulic head and gradients. A three-well site is being developed for tracer studies and hydraulic interference tests, so that effective porosity will be better known. Fossil packrat-midden studies are yielding data on climatic conditions at Yucca Mountain during the past 45,000 years. Lake-bed sediments in several playas north of the Nevada Test Site and in Walker Lake are being sampled for additional data pertaining to climatic and hydrologic conditions during the Quaternary Period. Studies of unsaturated-zone hydrology include analysis of matrix properties through laboratory tests on cores and in-situ measurement of matric potential and gas pressures. If Yucca Mountain is selected for Site Characterization (a formal phase of investigations, as defined by the Nuclear Waste Policy Act of 1982, Public Law 97-425), more detailed studies of the hydrology of Yucca Mountain will begin.

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